PROJECT FINAL REPORT

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BIANCHO Executive Summary

The BIANCHO project aimed to develop photonic components designed to significantly reduce power consumption at the component and system level in advanced communication systems. The intrinsic losses in telecom lasers and optical amplifiers (SOAs) are due to Auger recombination. Incremental approaches to overcome these problems have reached their limits. Dilute bismide alloys have the possibility to achieve a situation in the near- and mid-infrared where the fundamental energy gap is less than the spin-orbit-splitting energy at the valence band maximum, $E_g < \Delta_{SO}$, leading to the elimination of the dominant CHSH Auger recombination process in the alloy. There is also evidence that their energy gap and that of dilute nitride alloys has lower temperature dependence than conventional III-V alloys. BIANCHO therefore set four challenging objectives, to demonstrate:

- 1.5 μm $GaAs_{1-x}Bi_x$ lasers (x > 12%) with a reduced Auger contribution to the threshold current, to achieve threshold current density per quantum well (QW) < 100 A/Cm^2 and T_0 > 200 K
- 1.5 μm $GaAs_{1-x}Bi_x$ semiconductor optical amplifiers with the reduced Auger current allowing to raise the maximum operation temperature from 40 ^{o}C to 95 ^{o}C
- Dilute bismide-nitride electro-absorption modulators (EAMs) where the band gap shift with temperature is reduced from 0.5 nm/^{o}C to 0.1 nm/^{o}C
- High-speed GaAs-based dilute bismide photodetectors for telecom and wider THz applications.

The BIANCHO Consortium recognises that the results achieved, although world-leading, are nevertheless below the expectations and target specifications outlined in the Description of Work. Nevertheless, BIANCHO achieved the ***first-ever*** electrically pumped semiconductor laser including a dilute bismide (GaAsBi) active region. This was also the first GaAsBi laser operating at room temperature and the first bismide quantum well laser. By carefully designing the growth conditions, we were able to form high-quality GaBiAs single-quantum-well lasers with a bismuth incorporation of 2.2%.

The challenge however in growing dilute bismide alloys is to incorporate sufficient Bi in the active region to reach the condition where $E_g < \Delta_{SO}$, which we showed occurs once x > ~10%. It is generally easier to incorporate a larger Bi fraction using MBE rather than MOVPE. We therefore grew laser structures where the GaAsBi active region was grown using MBE at FTMC, while the barrier and cladding layers were grown using MOVPE at Marburg. This allowed us to drive the Bi composition to x = 6% in a $GaAs_{1-x}Bi_x$ active region, the highest Bi composition reported to date in any working laser.

Having established laser action at x = 6%, major effort was devoted to the development of GaAsBi/GaAs QWs with higher Bi compositions. PL was obtained from samples with x ~9%, of comparable quality to that obtained from laser material with x ~6%. This strongly indicates that lasing should be possible at x ~9%, although we were not able to demonstrate lasing action at this composition. Room temperature PL was also obtained from a $GaAs_{1-x}Bi_x$/GaAs QW structure with x ~11.5%, confirming the potential for laser action to be extended to this composition and beyond.

Overall, the project succeeded to study several samples where $E_g < \Delta_{SO}$. Temperature-dependent optical measurements on structures close to the $E_g = \Delta_{SO}$ resonance provided the first evidence for Auger suppression once $\Delta_{SO}>E_g$. This was achieved in both GaAsBi/GaAs and InGaAsBi/InP test structures.

Detailed studies were also carried out of the temperature dependence of the energy gap in GaAsBi/GaAs, GaInNAs/InP and GaAsBiN/GaAs devices. Evidence for ~50% reduction in the temperature dependence of the energy gap was found in some samples. However further measurements showed a large (~30 meV) inhomogeneous broadening of the band edge transition, limiting the usefulness of these alloys for use in EAMs.

Prior to the BIANCHO project, research on bismide-based semiconductors had been primarily materials based, with little progress towards device realisation. Overall, our work drove forward the growth and optimisation of dilute bismide alloys, including demonstration of the first electrically pumped dilute bismide lasers, and the first lasers with x > 6%, although not yet Auger-free lasers. Without question, we have opened and provided Europe with a lead in this field. The exploitation activities of the project participants include the first commercially available dilute bismide alloys, with GaAsBi layers being sold for improved efficiency terahertz sources and detectors by FTMC spin-off Teravil. Further opportunities have been identified and are being pursued by the BIANCHO partners in areas including; photovoltaics, ultrafast systems, mid-infrared sensing and spintronics.

Overall our work lays strong foundations for enhancing European competitiveness in the global telecommunications and other identified markets and ultimately leading to new high technology jobs for Europeans, based on the development and application of uncooled telecom and related components with significantly reduced power consumption both at the component and system level.

1. BIANCHO Concept and Objectives

The concept of BIANCHO is very simple – to provide a fundamental improvement in efficiency in semiconductor lasers and semiconductor optical amplifiers (SOAs) for telecommunications and data communications and so remove the need for power hungry thermoelectric coolers (TECs) to control the device temperature. The energy savings across Europe in the next generation broadband fibre to the home (FTTH) network alone, are estimated at more than 200MW from consideration of just the customers' optical network units (ONUs), approximately 40% of the total power. This improvement in efficiency can be provided by removing the non-radiative (Auger) recombination that dominates conventional InP based lasers and SOAs and accounts for (wastes) 80% of the input electrical power, and by substantially reducing the temperature dependence of the band gap in Electro-absorption modulators (EAMs), removing the need for temperature control. Theoretical modelling has shown that it is possible to design materials where Auger recombination is eliminated and materials with a lower temperature dependence of the band gap. BIANCHO targeted devices based on dilute nitride and bismide materials on InP and GaAs substrates to achieve these goals.

1.1 Socio-economic drivers

BIANCHO aimed at developing bismide- and nitride-based photonic components operating at telecomm wavelengths designed to significantly reduce power at the component and system level, and thereby enable unlimited bandwidth through integration, more optical processing and very high spectral-density photonic transmission. BIANCHO addresses a challenge which has been widely identified[1,2] as a key requisite for continued increase in communication bandwidth, namely reduced energy consumption and integration of component technologies. The project sought to develop improved lasers and optoelectronic devices for high temperature operation, thereby reducing or eliminating power-consuming active cooling.

The components and systems facilitated by the technology developed in this project will have much improved efficiency and thereby reduced energy consumption. Thermoelectric coolers (TECs) often account for over 80% of the power consumption of fibre optic modules. Through the direct & indirect effects of higher temperature operation, i.e. removing the need for TECs, the total power demand of components using this new technology can be reduced by at least an order of magnitude. Based on typical modules in FTTH installations this equates to around 2W per package. In the case of a Europe-wide rollout, removal of these TECs would reduce the potential power consumption of the system by several 100s of MW. The higher levels of photonic integration enabled by low-power devices, such as in the case of the integrated laser-modulator, would eliminate many ancillary components which are currently used to couple light between, and control, discrete laser and modulator functions.

These new components to be developed in BIANCHO could stimulate the development of applications with other significant social benefits, such as structural health monitoring of civil structures, industrial process and environmental monitoring and biomedical uses (data from Frost & Sullivan report on sensors[3] and ElectroniCast Corp report on harsh environment components[4]).

1.2 Technological driver

Numerous studies have shown the exponential growth in internet traffic over the last decade, driven by new user applications. The total electricity usage associated with internet traffic in the US in 2009 was estimated to be at least 1.2% (5 GW/annum), equivalent to the output of several nuclear power stations[5]. Much of this energy usage is associated with components which become increasingly

[1] Photonics 21, Towards a bright future for Europe – Strategic Research Agenda in Photonics, April 2006

[2] Source: http://www.the-infoshop.com/report/id66394-green-it_toc.html (accessed October 2009)

[3] Optical Sensors Technology Development and Growth Opportunities, Oct 2003, Frost & Sullivan

[4] Harsh Environment Fiber Optic Components and Systems, Jan 2004, ElectroniCast Corp

[5] M. C. Sanchez *et al*, Energy Policy, 36, 2098-2108 (2008) [and references therein].

inefficient with increasing temperature, and the need to employ energy-inefficient TEC coolers to stabilise this equipment. If the component efficiency remains unchanged then internet usage will rapidly start to dominate overall power demands.

Clearly these are trends which cannot be ignored and present an opportunity to develop greener devices with much improved performance. In the FTTX sector, low cost, high performance, uncooled devices in the customer's premises are the required competitive attributes, whilst in the core network the need to increase the available capacity per fibre as rapidly as possible is driving equipment suppliers towards more integrated high speed components and higher equipment densities. For most applications, uncooled operation means the ability of modules to operate up to 85 ^{o}C (chips to 95 ^{o}C) with only minor impairment from operation at 20 ^{o}C. A fundamental property of all currently available lasers and SOAs, at 1.55μm, related to the semiconductor band structure is the dominance of non-radiative recombination due to Auger recombination[6]. As temperature is increased, higher currents need to be provided to maintain output power. As most of this power is dissipated as heat rather than light, this leads to a thermal runaway situation that limits the maximum operating temperature. For electro-absorption modulators (EAMs), the band edge shifts to longer wavelength with increasing temperature at ~0.5nm/C, increasing the insertion loss for a given wavelength and consequently requiring energy-hungry temperature stabilisation electronics.

1.3 Device Concept and Motivation

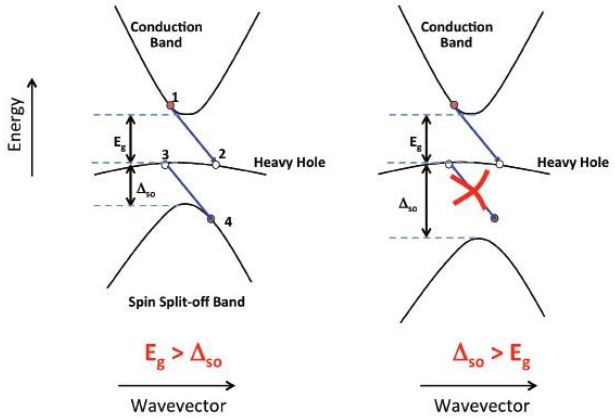

Figure 1: (Left) Schematic diagram showing the dominant Auger recombination loss mechanism present in conventional InP-based semiconductor lasers. Here a conduction electron (1) recombines with a valence hole (2), with the released energy exciting a valence hole (3) to the spin-split-off band (4) instead of creating a photon of light. (Right) Schematic diagram illustrating suppression of this Auger loss mechanism due to spin-orbit splitting exceeding the band gap energy, in which case the CHSH process is forbidden by conservation of energy, because the energy required to excite a hole to the spin-split-off band exceeds the energy produced by the electron-hole recombination.

Present semiconductor laser technology targeting 1.55μm is based upon InGaAsP/InP semiconductors. However, these devices suffer from two connected problems which dominate their performance. The threshold current is essentially the current required to switch on the laser. In InGaAsP/InP based lasers this current is ~5 times higher than one would ideally expect due to the presence of Auger processes which accounts for 80% of the current at room temperature, as demonstrated by the Surrey group[6]. In an Auger process (Fig. 1, left), when an injected electron (1) and hole (2) recombine, instead of producing a photon, they instead give their energy to excite a hole (3) to a higher valence state (4), from which it subsequently loses this energy in the form of heat. Thus, Auger leads to a dramatic decrease in efficiency and causes significant heating, which further exacerbates the problem. In addition to Auger, above laser threshold photons may be reabsorbed in the valence band, a process

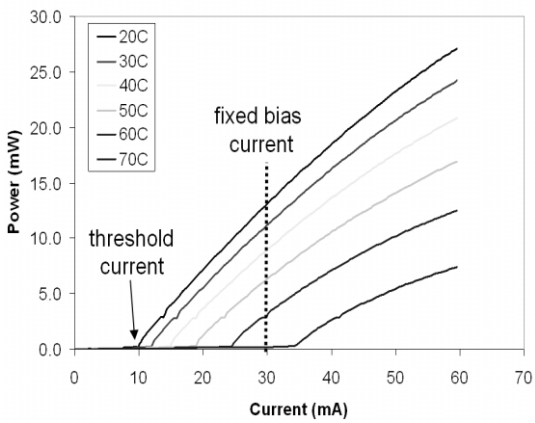

Figure 2 Optical Power versus current curves for a 1550nm InGaAsP/InP laser

[6] S. J. Sweeney *et al,* IEEE Phot. Tech. Lett. 10 8, pp1076-1078 (1998).

called inter-valence band absorption (IVBA). This causes a drop in output power and requires that the current into the device is increased to maintain a constant output power. Both Auger and IVBA are strongly temperature sensitive and strongly coupled[7] meaning that as the ambient temperature of the laser increases, the efficiency plummets, as evident from Figure 2. The temperature, T, sensitivity of the threshold current, I_{th}, can be approximated by an exponential function, such that $I_{th}=I_o\exp(T/T_o)$. Here I_o is a constant and T_o is the characteristic temperature where a high T_o corresponds to a low temperature sensitivity and vice-versa. In typical InGaAsP/InP lasers, T_o~50-60K around room temperature, dropping to ~40K above 50°C. For an ideal, quantum well based laser, T_o~300K around room temperature. However, for Auger dominated lasers the maximum attainable T_o is ~100K[8]. Conventional approaches to improve the performance of 1.55μm lasers have involved strategies to reduce the threshold carrier density, e.g. by using material systems such as InGaAlAs/InP and adopting a high number of quantum wells. However, in the best high quality InGaAlAs devices to date T_o~70-80K at room temperature[9].

The idea of the BIANCHO project is very simple – it aimed to provide a ***fundamental improvement in efficiency of semiconductor lasers and semiconductor optical amplifiers (SOAs) by suppressing the non-radiative Auger recombination*** that dominates conventional telecom lasers and SOAs. The dominant Auger loss mechanism that severely degrades the efficiency of conventional InP-based devices is schematically depicted in Figure 1 (left). Over many years, incremental approaches have sought to reduce the consequent inefficiencies without addressing their fundamental cause, which stems from the form of electronic band structure of the constituent materials in the active region of devices.

BIANCHO proposed a radical change of approach: to eliminate the troublesome Auger recombination process by manipulating the electronic band structure of the semiconductor materials through the use of novel materials. By exploiting the unique properties of bismuth-containing alloys, we aimed to essentially design Auger-free lasers which would lead to highly efficient and temperature stable lasers operating without the need for power hungry cooling equipment that current technology demands.

BIANCHO exploited two aspects of the electronic structure of bismide alloys. Firstly, the energy gap decreases very rapidly with bismuth composition, allowing growth of telecom lasers on a GaAs substrate. Secondly, and even more critically, the key idea behind the suppression of the dominant Auger loss process is schematically illustrated in Figure 1 (right). GaBi, in contrast to conventional III-V near-infrared materials, is predicted to have a very large spin-orbit splitting energy, Δ_{SO}, of the order of 2.2 eV between the valence band maximum and the lower lying spin-split-off valence band. Thus, by forming bismide alloys such as GaBiAs, InGaBiAs, and GaBiNAs one may achieve a semiconductor with a very large spin-orbit-splitting energy, Δ_{SO}. If the Δ_{SO} energy is engineered to exceed the band gap energy (E_g), Auger recombination will be reduced due to the conservation of energy rule. The goal of the BIANCHO team was the practical realization of this radical new idea.

Electro-absorption modulators (EAMs) are another of the key components of optoelectronic integrated circuits used in conjunction with semiconductor lasers for modulation. As discussed above, semiconductor lasers and SOAs are extremely sensitive to temperature in terms of their operating efficiency. Similar is true for EAMs. In an EAM an electric field applied across an active region material (e.g. quantum wells) may be used to selectively alter the transmission of the material. Thus, it may be used as a high speed switch. However, the wavelength (or energy) separation between the incoming photons and the band gap of the EAM material is key in determining the efficiency of the switching process. In conventional semiconductors, such as InGaAsP which are commonly used to make EAMs, the temperature dependence of the band gap, typically equivalent to ~0.5nm/^{o}C, causes the EAM efficiency to decrease with increasing temperature. This is due to the fact that the energetic separation relative to the light injected into the EAM decreases requiring a lower bias voltage on the EAM. This is a strict limitation of EAMs based

[7] S. J. Sweeney and P. J. A. Thijs, Laser and Electro-optics Society Annual Meeting (LEOS 2003), Tucson, USA, October 2003.

[8] E. P. O'Reilly and M. Silver, Appl. Phys. Lett., 63, pp3318-3320 (1993).

[9] S. J. Sweeney et al, Physica Status Solidi (b), 241, pp3391-3398 (2004).

on conventional III-V semiconductors whose band gap varies with temperature in a known manner (characterised through the Varshni expression[10]). Again, this is clearly a case where slight modifications to existing materials will only offer *incremental improvements in performance with diminishing returns*. In BIANCHO, we investigated to exploit the unusual and unique properties of dilute nitride (and bismide) materials which have a much reduced temperature dependence of the band gap due to an effect known as band anti-crossing[11]. It had been proposed that the incorporation of dilute (~ few %) of either nitrogen or bismuth offers the possibility of achieving a temperature coefficient of the band gap ~0.1nm/^{o}C[12], thus maintaining a ***higher EAM efficiency over a wide temperature range***. In addition to removing the requirements of temperature control for lasers and SOAs, this approach to producing EAMs offers the opportunity to completely eliminate temperature control from the system giving rise to substantial energy savings.

BIANCHO aimed to develop **higher efficiency, versatile** photonic components in the 1.3 – 1.6 μm range exploiting the unique properties of dilute nitride and dilute bismide alloys. The dilute nitride alloys were to be grown on InP substrates, compatible with existing processing capabilities for telecommunications devices, while the higher-risk components using dilute bismide alloys were to be demonstrated on GaAs and InP substrates. We worked to develop new GaInBiAsN/InP devices at 1.3μm and 1.55μm with enhanced properties. The electro-absorption modulators targeted reduced temperature dependence of the energy gap, enabling stable uncooled operation over an extended temperature range. The lasers and SOAs targeted improved operating parameters, e.g. increased internal quantum efficiency, decreased laser threshold currents, tailorable polarisation and improved thermal stability. This would enable higher temperature operation with lower cooling power demands at longer wavelengths.

Finally, BIANCHO also addressed the question of development of ***bismide-based photodiodes***, thus stimulating the switch-over of whole telecom component technology to this material system, and also opening new opportunities in THz emission and detection. The energy band gap of GaAs can be narrowed to values close to the photon energies corresponding to the optical communication windows already by introducing dilute amounts of Bi. Moreover, because the effect of Bi on the energy band structure is mainly limited to the valence band, no band off-sets and no additional barriers will be present in the conduction band of bismide/GaAs heterostructures, which can then essentially improve the device characteristics of p-i-n diodes, avalanche photodiodes, and uni-travelling carrier photodiodes. The development of these devices in BIANCHO is of value not just in their own right but also as an important support towards the development of device-quality energy-efficient bismide-based Auger-free lasers and EAMs for uncooled operation.

In summary, previous work has shown that even the best InP-based 1.55μm lasers suffer from Auger recombination whereby the energy of injected carriers is lost as heat rather than by producing light[6]. Auger recombination is very sensitive to the band structure, particularly the conduction band effective mass and the spin-orbit splitting. There is little flexibility within the InGaAlAs or InGaAsP systems to manipulate the band-structure, hence we sought to develop Bi and N as alternative group V elements to tailor the band-structure to our advantage. The incorporation of nitrogen and/or bismuth brings several advantages, some of which were outlined above.

The proposal was very timely. It was only recently that theoretical work has developed a first understanding of what is required to overcome the Auger recombination mechanism, and that new materials had started to be explored for practical realisation. Bismides and nitrides had been demonstrated to have suitable properties – BIANCHO sought to focus on design and growth of material of good enough quality to make good devices. The world leading epitaxy partners in BIANCHO were very well placed to undertake this.

Because dilute nitride and bismide III/V semiconductors are both metastable due to the significantly different covalent radius of the alloying elements N and Bi respectively, they have to be grown under extreme non-equilibrium conditions. Generally, this is done by lowering the growth temperature. This is straight-forward in MBE, but can only be done in MOVPE when metal organic

[10] Y. P. Varshni, Physica, 34, 149 (1967).
[11] A. Lindsay and E.P. O'Reilly, Phys. Rev. Lett. 93, 196402 (2004)
[12] Yoshimoto et al, pss 243, 1421 (2006)

precursors are used, which show significant decomposition at those low temperatures. Phillips University Marburg (PUM) has with this respect a worldwide unique position, as they have close links to Dockweiler Chemicals GmbH (Marburg), a spin-off company of PUM, which is the world-market leader in liquid group V metal organic precursors, which decompose at considerably lower temperatures than the corresponding group V hydride precursors. In common projects with this company PUM also has experience in purifying and testing novel metal organic compounds for epitaxy. This was important for the N-precursors but especially so for the entirely novel bismuth precursors.

The specific aims of the BIANCHO project were therefore:
(1) Demonstration at telecommunications wavelengths of uncooled electro-absorption modulators based on dilute nitride alloys
(2) Demonstration of uncooled semiconductor optical amplifiers and lasers based on dilute nitride alloys
(3) Demonstration of high-speed photodetectors and laser structures based on dilute bismide alloys
(4) Growth and demonstration of laser and SOA structures incorporating dilute amounts of nitrogen and bismuth on InP for future uncooled photonic devices

The need for the uncooled devices was determined primarily by the demands of end users and their specifications were provided to the project by CIP from knowledge of the requirements of telecom system integrators. The devices targeted are the key components required to achieve the major reduction in power consumption which is necessary for the development of fibre access networks and very high spectral-density photonic transmission in core networks. The involvement of CIP offered an excellent means of validation of the components and a clear route towards their future commercialisation and widespread implementation.

2. Main S&T Results and Foregrounds

2.1 Introduction

BIANCHO addressed a challenging question. The project aimed at developing dilute bismide and nitride photonic components operating at telecomm wavelengths designed to significantly reduce power at the component and system level, and thereby enable unlimited bandwidth through integration, more optical processing and very high spectral-density photonic transmission. BIANCHO addresses a challenge which has been widely identified as a key requisite for continued increase in communication bandwidth, namely reduced energy consumption and integration of component technologies.

This requires the development of entirely new **higher efficiency, versatile** photonic components in the 1.3 – 1.6 μm range exploiting the unique properties of dilute nitride and bismide alloys. It included some of the first growth of dilute nitride alloys on InP substrates, compatible with existing processing capabilities for telecommunications devices, as well as leading the development and demonstration of higher-risk components using dilute bismide alloys on GaAs and InP substrates. We sought GaInBiNAs/InP devices at 1.3μm and 1.55μm with enhanced properties. This included electro-absorption modulators with reduced temperature dependence of the energy gap, enabling stable uncooled operation over an extended temperature range. The development of lasers with improved operating parameters, e.g. increased internal quantum efficiency, decreased laser threshold currents, tailorable polarisation and improved thermal stability required first the development and demonstration of device-quality dilute bismide alloys containing up to and beyond 10% Bi in $GaBi_xAs_{1-x}$ quantum well structures. BIANCHO partners have led the development of this material system, demonstrating the first electrically pumped bismuth-containing semiconductor laser, which was also the first bismide laser to operate at room temperature, and subsequently pushing the Bi content in working lasers to record levels.BIANCHO partners also demonstrated the

potential of dilute bismide alloys for THz emission and detection. This latter work is now being exploited byTeravil, which is a spin-off SME from the FTMC group. Teravil are already producing photoconductive THz emitters and detectors based on GaAsBi epitaxial layers as well as whole THz time-domain-spectroscopy systems using these components activated by Yb doped fiber laser pulses (see http://www.teravil.lt/products.php).

BIANCHO made major progress in developing and implementing dilute bismide alloys for a range of device applications. Significant progress was also made in the first two years of the project on the development of dilute nitride alloys grown on InP. The primary objective of the project was to establish materials of sufficient quality to demonstrate Auger-free $GaAs_{1-x}Bi_x$/GaAs lasers emitting at 1.55 μm (with x ~ 12%). In the case that it proved too difficult to obtain high quality GaAsBi with high Bi content, two further growth routes were investigated, which would require less Bi in the active region:

- growth of GaNAsBi/GaAs structures emitting at wavelengths > 1.55 μm (x < 10%),
- growth of GaInAsBi/InP structures emitting at wavelengths > 2.4 μm (x >~ 5%).

Although BIANCHO did not reach the objective to incorporate sufficient Bi to demonstrate Auger-free $GaAs_{1-x}Bi_x$/GaAs lasers emitting at 1.55 μm, world-leading progress was demonstrated in:

- Dilute nitride and bismide ***material growth and characterisation*** for optimized device fabrication
- Development of ***theoretical models*** suitable to describe dilute bismide materials and devices
- ***Device fabrication and demonstration***
- Elucidation of the ***physics of bismuth-containing devices*** and
- ***Engineering and optimisation of device characteristics***.

Highlights of our achievements are summarised in the next sub-section, with more detail of the key results in each of these areas then presented in the following subsections. Section 2.3 describes the main materials and device results obtained using MBE growth, while Section 2.4 highlights the main achievements using MOVPE growth. Section 2.5 overviews some of the key theoretical methods developed to analyse the electronic structure of dilute bismide and bismide-nitride alloys. Finally section 2.6 summarises the key results obtained regarding device physics and engineering. Overall, we conclude that the BIANCHO partners have driven the development of dilute bismide materials and devices to their current level of capability. Further work is required to reach the ultimate objective of Auger-free laser operation, but BIANCHO has provided the path to achieve this very challenging and technologically important aim.

2.2 Overview of BIANCHO progress and achievements

Dilute nitride and bismide material growth and characterisation for optimized device fabrication

BIANCHO led the growth and development of dilute bismide alloys, based on the extensive previous experience of FTMC in the MBE growth of shorter wavelength dilute bismide alloys and the experience of PUM in MOVPE growth of highly mismatched dilute nitride alloys on GaAs. Achievements of the project included:

- Demonstration that spin-orbit splitting can exceed energy gap in dilute bismide based 1.55 μm emitters
- Establishment of hybrid growth capability, where GaAsBi active region grown by MBE in Vilnius, with cladding layers grown by MOVPE in Marburg; lasing obtained from quantum wells containing up to ~7% Bi
- Development at Marburg of growth models for GaAsBi, leading to understanding that Bi incorporation dominated by Bi surface coverage
- Analysis of how Bi incorporation depends on growth temperature, growth rate & V/III ratio allowed us to incorporate 7.4% Bi in GaAsBi structures, grown at 375°C by MOVPE;

however it did not prove possible to do this on the n++ AlGaAs cladding layers required in a laser structure

- Growth of high structural quality GaNAsBi/GaAsand type II GaNAs/GaBiAs structures
- Successful growth of GaInAsBi quantum wells on InP substrates by MBE, with room temperature photoluminescence at wavelengths up to 2.4 μm.
- Establishment of growth conditions for high quality GaInNAs/GaInAsP structures
- Growth of GaAsBi quantum well structures, with Bi composition up to x ~9%, and room temperature PL amplitude comparable to that measured in 6% QW laser structures; electroluminescence observed in samples containing up to ~9% Bi
- Growth of GaAsBi quantum well structures, with Bi composition x ~11.5%, with room temperature PL amplitude indicating the potential for laser action to be extended to this composition and beyond.

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Development of theoretical models

- Development of quantitative band structure models for dilute nitride and bismide alloys, and application to material analysis and device design.
- Validation of tight-binding and k.p-related models for the band structure of dilute bismide, dilute bismide-nitride, and dilute indium-bismide alloys of GaAs
- Application of 12-band k.p model for gain and loss analysis in Ga(N)AsBi/GaAs and GaInAsBi/InP quantum well laser structures using band structure models developed within project.
- Design and growth of dilute nitride laser and EAM structures

Device Fabrication and characterisation

- Fabrication and initial characterisation of MOVPE-grown dilute bismide broad area laser structures, demonstrating first electrically pumped dilute bismide lasers worldwide, and first bismide laser to operate at room temperature
- Fabrication and initial characterisation of hybrid MBE/MOVPE dilute bismide broad area laser structures, demonstrating lasing at highest Bi composition found to date (≥6%) in dilute bismide laser structure
- Fabrication and electroluminescence measurements of diodes with Ga(AsBi)/GaAs quantum wells with up to 9%Bi.

Device Physics and Engineering

- Measurement of weaker temperature dependence of peak wavelength in GaBiAs LED compared with GaAs.
- Identification of critical Bi fraction for Auger suppression
- Measurement of type-I band alignment for GaBiAs/GaAs, in agreement with theoretical modelling within BIANCHO.
- Design and analysis of GaAsBi/(Al)GaAs laser structures,
- Detailed band structure calculations highlighting critical bismuth and nitrogen concentrations to achieve $\Delta_{SO} > E_g$
- Application of 12-band k.p model for gain and loss analysis in GaNAsBi/GaAs and GaInAsBi/InP quantum well laser structures using band structure models developed within project.
- Electrical and optical characterisation of MOVPE grown GaAsBi, GaAsBi/GaNAs and GaNAsBi device structures at different temperatures, with room temperature lasing observed in GaAsBi/GaAs devices.
- Initial characterisation of MBE/MOVPE devices with low temperature lasing achieved
- Extensive spectroscopic investigations of GaInAsBi, GaNAsBi and GaNAs/GaAsBi samples, using theoretical models to assist analysis
- Detailed theoretical and experimental analysis of initial bismide lasers, providing material parameters and input for design and analysis of higher Bi content devices.

2.3 MBE Growth of Novel GaBiAs Materials and Devices

2.3.1 MBE growth of GaAsBi/GaAs layers

Two technological approaches were investigated for MBE growth of bismide layers with enhanced Bi composition. Using the first of these approaches, GaAsBi layers were grown by a migration-enhanced epitaxy (MEE) technique – a method proposed by Horikoshi et al. for growing epitaxial layers of GaAs and AlGaAs at temperatures below 300 °C[13]. The key to the growth of epitaxial GaAs at low temperatures is to minimize the excess of arsenic and to enhance the surface mobility of gallium adatoms. In MEE, Ga atoms are supplied on the growing surface under As-free conditions or at very low As beam pressures. Under these conditions, Ga atoms are expected to migrate along the surface and to find stable sites even at significantly reduced growth temperatures. Three different sequences of group III and V atomic layer deposition have been used for GaAsBi layer growth: Bi atoms were supplied to every second, every third, and every fifth group V element atomic layer. It should be pointed out that the overall duration of each element supply during one GaAsBi monolayer growth cycle and different growth sequences remained unchanged.

GaAsBi layers and multiple quantum well structures have been grown on GaAs substrates by MEE at temperatures as low as 140 °C. Alloys with more than 10% of Bi – a composition necessary for the applications in a 1.55 μm optical communication window – were obtained. GaAsBi layers were of high structural uniformity and their surfaces were nearly free from Bi droplets. Some out-diffusion of bismuth into the growing GaAs barrier layer reduces the abruptness of GaAsBi/GaAs interfaces; this problem could eventually be solved by optimizing the growth conditions or by growing additional diffusion barriers at these interfaces. The GaBiAs/GaAs MQW structure grown at the temperature of 160 °C and consisting of four 5-nm-thick GaAsBi quantum wells surrounded by 30-nm-wide GaAs barriers is shown on Fig. 3. The technological conditions for the MQW structure growth were selected attempting to achieve both a large Bi content and the lowest interface roughness. (2 × 1) and (1 × 3) surface reconstructions were observed during the growth of GaAsBi QWs and GaAs barriers, respectively.

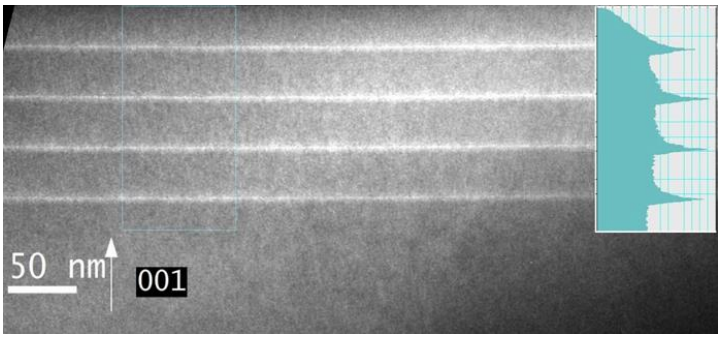


Fig. 3. Chemically sensitive (002) TEM dark field image of Ga(BiAs)/GaAs multiple quantum well structure and the line-scan across the TEM image.

Structural quality of GaAsBi layers grown by MEE remained excellent even for the lowest growth temperatures, however short carrier lifetimes of the low-temperature grown material were effectively suppressing the photoluminescence effect. These short non-radiative recombination times are caused by intrinsic, stoichiometry related structural

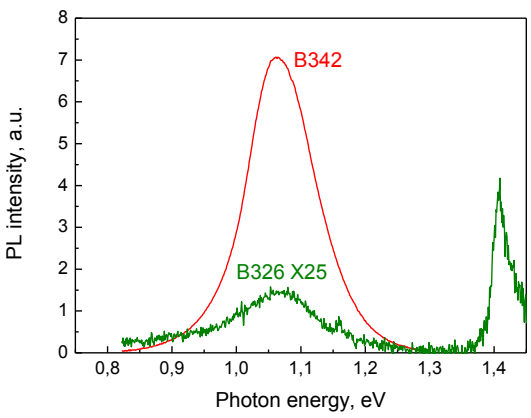


Fig.4 . PL spectra of two GaAsBi/GaAs QW samples.

[13] Y. Horikoshi, M. Kawashima, and H. Yamaguchi, Migrati 27(2), 169–179 (1988), http://dx.doi.org/10.1143/JJAP.27

defects as antisites and vacancies, and their density is extremely sensitive to the technological conditions of the epitaxial growth. On the other hand, Bi incorporation into the layer grown by MEE at higher growth temperatures started to saturate earlier. Therefore, traditional molecular-beam-epitaxy process with all molecular sources simultaneously opened during the growth was selected for bismide layer growth at higher substrate temperatures.
For optimizing technological conditions of GaAsBi/GaAs quantum well (QW) growth a series of 14 growth runs was performed on semi-insulating (100) GaAs substrates. At first, 100 nm-thick GaAs buffer layer was grown at 600°C substrate temperature. The width of QW in all samples was ~ 7 nm. The growth rate was ~0.25 μm/h. Quantum wells in all samples were grown at 330°C substrate temperature, using arsenic to gallium beam equivalent pressure ratio close to 1.1 and Bi flux constant and equal to ~$4.5\cdot10^{-8}$). The width of the barriers and the spacers was 30 nm and 15-20 nm, respectively. The crystalline structure was monitored during the growth by reflection high-energy electron diffraction (RHEED); the quality of the grown samples was checked by the atomic force microscopy and the spectral photoluminescence measurements.

Several different experiments leading to the enhancement of PL signal were performed such as: i) p-type doping of the barrier layers[14], ii) GaAs barrier layer growth at higher temperatures leading to in-situ annealing of bismide well layer, iii) uniform and delta doping of the barrier layers with beryllium. The results of these technological experiments were compared by measuring photoluminescence spectra of the samples at room temperature. The position of the PL peak was changing in the range from 1.05 eV to 1.17 eV, which for 7 nm wide quantum well has corresponded to the bulk energy band gap of ~1 eV or the Bi content in the well region of approximately 6 %. On the other hand, each new change in the growth technology has led to a smaller or larger improvement of the PL intensity; the exception to that rule was the use of AlGaAs instead of GaAs barriers, which did not give an expected positive effect. Total enhancement of the PL intensity was by more than 100 times; it is illustrated on Figure 4, where PL spectra for two samples: B326 (nondoped barriers grown at the same temperature as the well) and B342 (Be-doped barriers grown at 450°C) are presented.

2.3.2 MBE growth of GaInAsBi/InP layers

The GaInAsBi material system has potential for an even wider range of applications with a variety of wavelengths that can be achieved on InP substrates with the possibility of Auger suppression with smaller Bi fractions. Quaternary GaInAsBi layers were grown by MBE on InP substrates with Bi content up to 7%[15]. Energy band gap of the material was as low as 0.5 eV; the layers showed photoluminescence signals at the mid-infrared wavelengths up to 3 μm at liquid-nitrogen temperature. The band-gap temperature dependence was shown to be significantly weaker in Bi-containing GaInAs layers than that in GaInAs buffer layers.

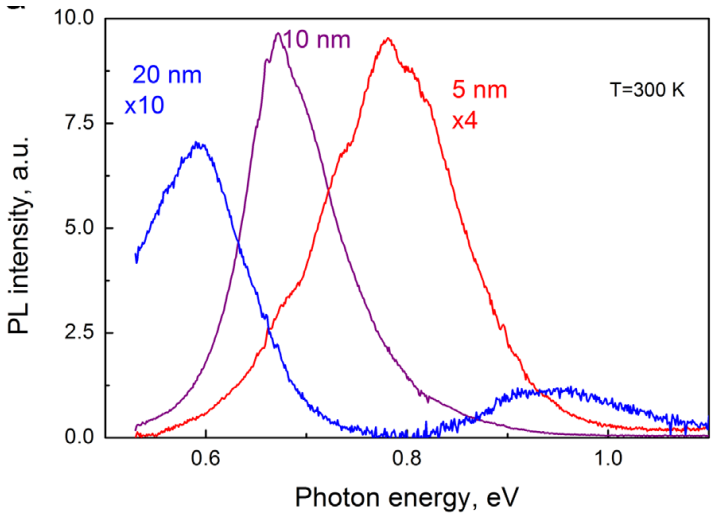


Fig. 5 PL spectra of three SQWs with different thicknesses measured at room temperature.

More recent GaInAsBi/InP samples

[14] V. Pačebutas, R. Butkutė, B. Čechavičius, J. Kavaliauskas, A. Krotkus, Photoluminescence investigation of GaAs1−xBix/GaAs heterostructures, Thin Solid Films, 520, 6415-6418 (2012).
[15] J. Devenson, V. Pačebutas, R. Butkutė, A. Baranov, A. Krotkus, Structure and optical properties of InGaAsBi with up to 7% bismuth, Appl.Phys.Express, 5, 015503–015513 (2012).

from FTMC were QW samples comprising of 5nm, 10 nm, and 20nm GaInAsBi QWs containing 3.7%Bi within an AlInAs barrier[16].Optimal growth conditions established for $Ga_{0.47}In_{0.53}As_{1-x}Bi_x$ layers with x=0.037—the substrate temperature of 240°C and the As/Bi BEP ratio of 12—were selected as the starting point for the well growth. Later on, the structures with a larger Bi content in the well layer were grown by varying As/Bi BEP ratio from 12 to 6 (by increasing the Bi flux, As flux is kept constant or slightly lower).The bottom barrier layer was 160nm-thick $Al_{0.48}In_{0.52}As$ lattice-matched to the InP substrate and grown at the temperature of 460 °C. After the growth interruption and decreasing of the substrate temperature down to 240 °C, GaInAsBi SQW layer was grown. Room temperature PL spectra measured on three samples with QWs of a different thickness are presented on Fig. 5 suggesting improvement in growth quality. A TEM image of 10 nm thick QW is presented in Fig. 6. Good homogeneity of the $Ga_{0.47}In_{0.53}As_{1-x}Bi_x$ quantum wells without distinct segregation of bismuth can also be evidenced from this image.

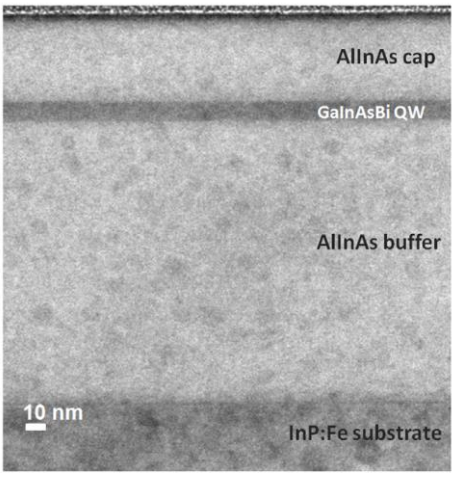


Fig. 6. TEM cross-sectional image of the GaInAsBi/AlInAs quantum well structure.

2.3.3 Bismide based devices

Due to the large energy band gap narrowing after incorporating into GaAs relatively small amounts of bismuth dilute bismide compounds prospective for infrared (IR) optoelectronic devices grown on GaAs substrates. Moreover, GaAsBi based laser diodes are envisaged to have smaller Auger losses than traditional telecom laser diodes[17], and ultrafast photoconductors fabricated from this material have been already shown their superb performance as terahertz radiation emitters and detectors activated by femtosecond IR laser pulses[18]. Uni-Travelling-Carrier Photo-Diodes (UTC-PD) with absorber layers from GaAsBi were grown on GaAs substrates and characterized in this work[19]. Their spectral sensitivity was reaching the wavelengths of 1.3 μm; the photosensitivity at 1064 nm was about 15 mA/W, which is comparable to the values of this parameter obtained on p-i-n diodes with bismide absorber layer of a similar thickness. Device characteristics can be improved by further developments in relatively new dilute bismide technology both in terms of the material composition and the carrier mobility. GaAsBi based

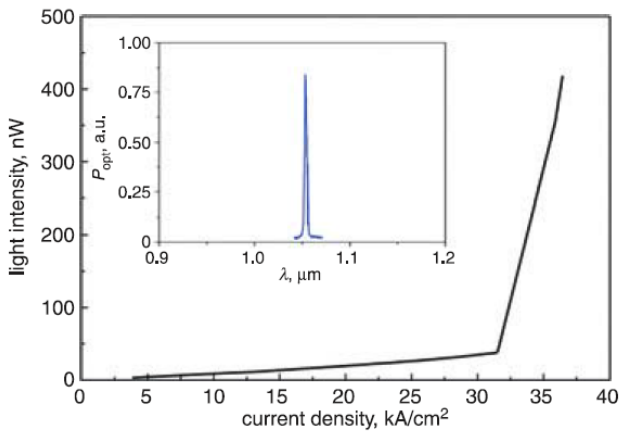


Fig. 7. Room temperature light-current and spectral (inset) characteristics of the diode laser fabricated from the wafer B343.

[16] R.Butkutė, V. Pačebutas, B. Čechavičius, R. Nedzinskas, A. Selskis, A. Arlauskas, A. Krotkus, Photoluminescence at up to 2.4 μm wavelengths from GaInAsBi/AlInAs quantum wells, Journal of Crystal Growth, 391, 116–120 (2014).
[17] S. Sweeney, S. Jin, J Appl Phys., 113, 043110 (2013).
[18] V. Pačebutas, A. Bičiunas, S. Balakauskas, A. Krotkus, G. Andriukaitis, D. Lorenc, A. Baltuška, Appl. Phys. Lett., 97, 031111 (2010).
[19] A. Geižutis, V. Pačebutas, R. Butkutė, P. Svidovsky, V. Strazdienė, A. Krotkus, Growth and characterization of UTC photo-diodes containing $GaAs_{1-x}Bi_x$ absorber layer, Solid-State Electronics, 99, 101-103 (2014).

optoelectronic devices open the door to previously unattainable for the cost effective GaAs technology in infrared spectral region.

Fabrication of the laser diodes with bismide active layers were the main objective of this project. To increase the Bi concentration a combined MOVPE/MBE growth approach was used in a three-stage approach. Initially, the lower (n-doped) cladding is grown by MOVPE at PUM. This is then sent to FTMC for MBE growth of the bismide-containing QW active region, after which it is finally sent back to PUM for MOVPE growth of the (p-doped) upper cladding. Two 3QW devices (samples B343 and B344) with ~6% Bi were discussed in detail in [20]. Room temperature lasing from device B343 is illustrated by experimentally determined characteristics presented in Fig. 7. The B383 QWs contained ~8%Bi, but devices had very weak light output (CW facet emission spectra were detectable only at very low T using an optical spectrum analyzer).

A further growth iteration using the hybrid approach was attempted to increase the bismuth fraction. The samples B431 and B432 had three 12-nm wide QWs with 7 to 8%Bi, whereas samples B514, B521, B522 had 5 quantum wells of 8 nm thickness and the estimated Bi content in the range from 6 to 7.5 %Bi. From all these samples, only laser diodes fabricated from the wafer B521 have shown the laser effect. The lasing wavelength at liquid nitrogen temperature was close to 1100 nm, as shown in Fig. 8. It has been found that the main obstacle for obtaining devices lasing at longer wavelengths is the presence in as grown MQW structures with larger Bi content of deep pits reaching all the way to the substrate and inducing optical losses in the laser waveguide. Numerous attempts to reduce the number of these pits by more finely adjusting the bismide layer growth conditions were not successful as yet.

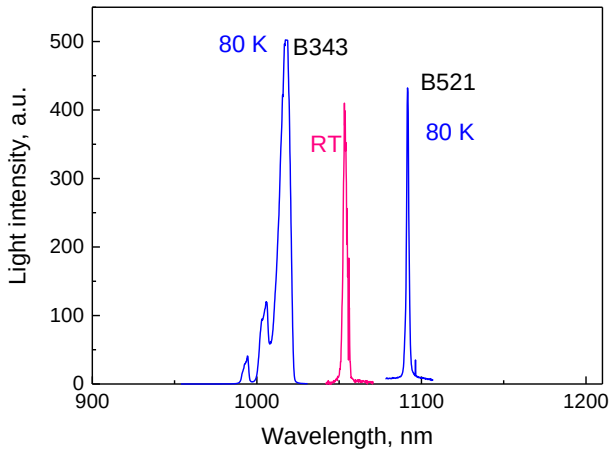


Fig. 8. Lasing spectra of two GaAsBi/GaAs MQW laser diodes.

2.4 MOVPE Growth of Novel GaBiAs Materials and Devices

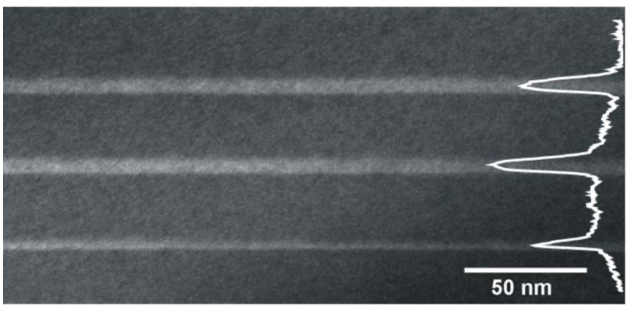
2.4.1 GaAsBi growth by MOVPE

Ga(AsBi) growth at Marburg took place by using metal organic vapour phase epitaxy (MOVPE). A commercially available reactor (AIX 200) at reduced pressure of 50 mbar using hydrogen carrier gas was used. All liquid metal organic precursors (triethylgallium (TEGa), tertiarybutylarsine (TBAs), trimethylbismuth (TMBi)) were used. Bismuth content and layer thicknesses were determined from dynamical modelling of high resolution X-ray diffraction (HR-XRD) ω-θ scans. cw – PL (photoluminescence) measurements were used for comparison to confirm the Bi-content of the layers.

TEM (transmission electron microscopy) has been very helpful in investigating the growth mechanism of dilute bismide alloys. This understanding in turn led to the possibility to grow high-quality Ga(BiAs)/(AlGa)As layer and laser structures using specific temperature ramping processes.

[20] R. Butkutė, A. Geižutis, V. Pačebutas, B. Čechavičius, V. Bukauskas, R. Kundrotas, P. Ludewig, K. Volz, and A. Krotkus, Multi-quantum well Ga(AsBi) laser diodes with more than 6% of bismuth, Electron. Lett., 50, 1155-1157 (2014).

Fig. 9(a) exemplarily shows a chemical sensitive (002) dark field, from which one can conclude, that the crystalline quality of the layers is very good. Moreover, the first grown Ga(AsBi) quantum well is much thinner than the other two. This is a hint that surface segregation and coverage plays a large role when growing this material system. From several of these investigations using samples grown under different conditions, we were able to derive a growth model, which is schematically depicted in Fig. 9(b). At the very beginning of the Ga(AsBi) growth, the Bi does not incorporate but stays at the surface and acts as a surfactant until a certain surface coverage is reached. After a certain surface coverage, depending on growth parameters, the Bi incorporation takes place in a linear behaviour. This is the situation where controlled growth of Ga(AsBi) is possible. With further Bi offering, the Bi concentration saturates, which leads to a limitation of the Bi incorporation and also to a reduced growth rate of Ga(AsBi)-layers, as the superficial Bi is riding at the surface. The saturation Bi-concentration depends on growth conditions (e.g. temperature).



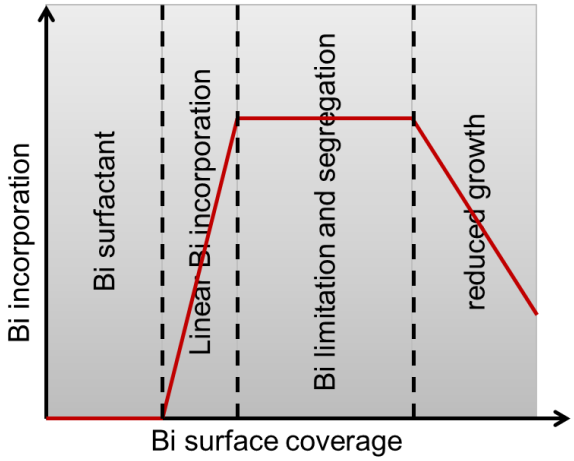


Fig. 9 (a) Cross-sectional TEM DF (002) image of Ga(AsBi)/GaAs 3xQWs grown at 400 °C with a small TMBi supply. The first Ga(AsBi) QW is thinner than the other two.

(b) Scheme of the Bi-incorporation, depending on the given Bi surface coverage during the MOVPE growth process

Many factors influence the Bi content of the material, including the bismuth supply, growth rate and growth temperature. Key factors to increase the Bi-fraction in the crystal are reducing the growth temperature and increasing the growth rate. In the following, growth characteristics at 400 as well as 375 °C will be exemplarily shown.

T_{growth} = 400°C

Ga(AsBi) bulk samples were first grown at 400°C with a GaAs cap layer grown at 625°C. The TMBi supply during growth was varied and the resulting Bi content and growth rate are plotted in Figure 10. The set of samples plotted with the black markers were grown with constant TEGa partial pressure of 4.2E-2 mbar and TBAs/TEGa = 1.7. There is initially a linear increase in the Bi content with increasing TMBi supply, then for higher TMBi supplies the Bi content reaches a maximum of ~3.8% and remains approximately constant. When the TMBi supply is increased too much, Bi droplets form on the surface as the extra Bi cannot be incorporated and segregates to the surface during growth. The growth rate initially decreases with increasing TMBi supply, levelling out as the Bi content reaches the maximum value. This may be due to the increased Bi surface coverage during growth reducing the diffusion of atoms to the growth surface or reducing the decomposition of precursors. This also might be due to hydrocarbon restgroups (from low temperature growth) blocking active surface sites.

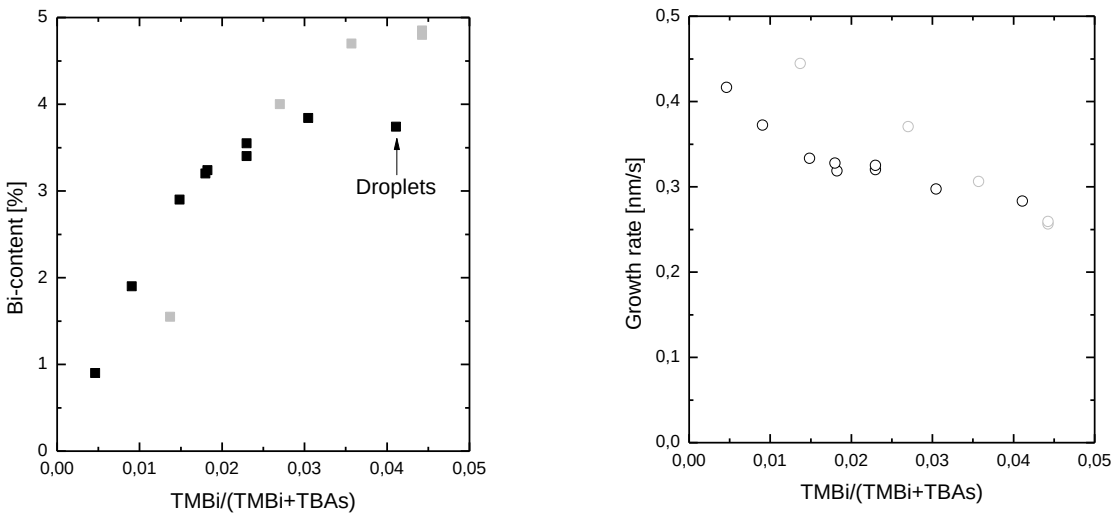


Figure 10: Bi-content (left) and growth rate (right) of GaAsBi bulk layers grown at 400°C with TEGa =4.2E-2 mbar, TBAs/TEGa = 1.7 (black markers) and TEGa = 8.0E-2 mbar, TBAs/TEGa = 0.7 (grey markers)

The set of samples plotted with grey markers were grown with a higher TEGa partial pressure of 8.0E-2 mbar in order to increase the growth rate and a lower ratio of TBAs/TEGa = 0.7 was used. The same trend of increasing Bi content with increasing TMBi supply is seen, again beginning to reach a plateau at higher TMBi supplies. In this case it is possible to reach a higher maximum Bi content of ~5% whilst keeping a droplet free surface.

T_{growth} = 375°C

In order to increase the Bi content further, a lower growth temperature of 375°C was used. A set of samples were grown with constant TEGa partial pressure of 8.0E-2 mbar and TBAs/TEGa = 1.0, and the TMBi supply was again varied. The resulting Bi content is plotted in Figure 11. The same trend is seen as in the 400°C samples; initially there is a linear increase in Bi content with TMBi supply until a maximum incorporation is reached and the Bi content remains constant. For this set of samples the maximum Bi content is ~7%, which is greater than was achieved at 400°C.

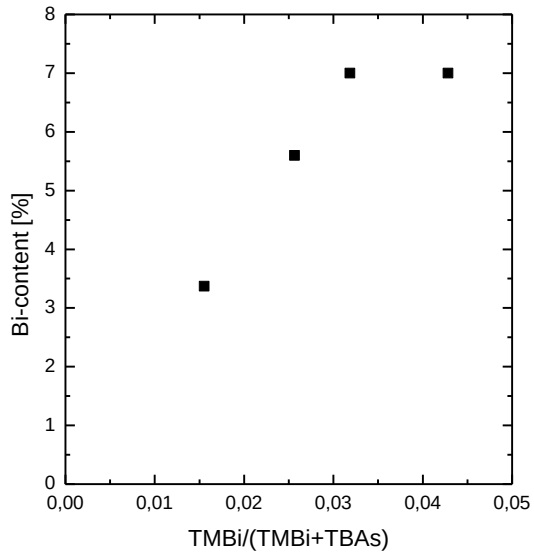


Figure 11: Bi content of GaAsBi bulk layers grown at 375°C with TEGa = 8.0E-2 mbar, TBAs/TEGa = 1.0

Figure 12 shows the PL emission of this sample at room temperature. It is remarkable that all samples grown by MOVPE showed room temperature PL with the PL intensity increasing with increasing Bi-fraction. It also should be noted that the Carbon impurity level in the Ga(AsBi) layers drops with increasing Bi-fraction. This points towards a surfactant effect of the Bi and is very important as usually at these low growth temperatures Carbon incorporation from the MO precursors is a severe issue in MOVPE growth.

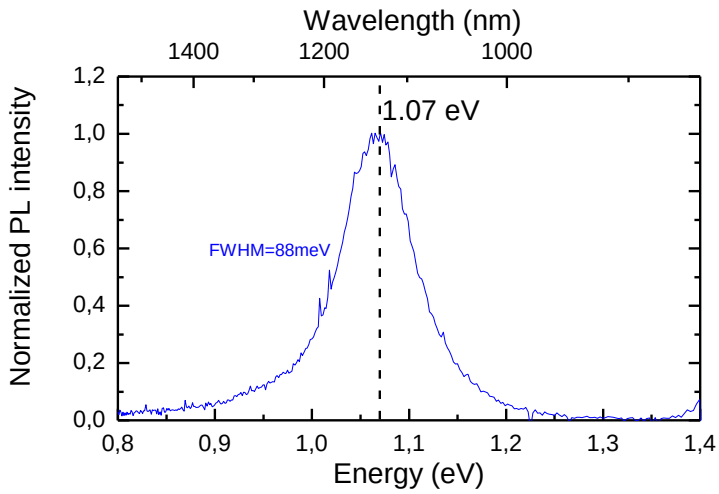


Figure 12: PL spectrum of the sample grown by MOVPE which had the largest Bi-fraction (~ 7% from XRD).

Using the growth conditions explained above, several edge emitting laser structures have been grown. The characteristics of these devices are summarized in 2.6.

We also looked into the Ga(AsBi) growth using different MO precursors, like tritertiarybutyl bismuth and triisopropyl bismuth in addition to studying the growth with TMBi. From these experiments it could be clarified that not the decomposition of the precursors, but hydrocarbon restgroups accumulating at the surface under the low temperature growth conditions and/or a Bi-film riding the surface are the factors limiting the Bi-incorporation.

2.4.2 GaNAsBi growth by MOVPE

Extensive investigations into the growth of Ga(AsBi) as described above have shown that at low growth temperatures of 375 – 400°C it is possible to produce samples with Bi content up to around 7% and good crystal quality. Growth of Ga(NAsBi) was therefore studied around this temperature range. Again, all liquid metal organic precursors (triethylgallium (TEGa), tertiarybutylarsine (TBAs), trimethylbismuth (TMBi), unsymmetric dimethylhydrazine (UDMHy)) were used.

Dynamical simulations of high resolution X-ray diffraction (HR-XRD) data for the quaternary material Ga(NAsBi) only allow a linear relationship between Bi and N content to be established, not absolute values for each. In order to investigate the effect of N incorporation on Bi incorporation, a sample was grown with Ga(AsBi) and Ga(NAsBi) layers where the only difference in growth conditions was the addition of nitrogen to the second layer with the ratio of partial pressures UDMHy/TBAs = 1. From the SIMS profile of this sample (figure 13) it can be seen that the Bi concentration in both layers is approximately constant, independent of the addition of nitrogen. It is therefore assumed when performing subsequent XRD simulations that the Bi content will be the same as in an equivalent N-free sample.

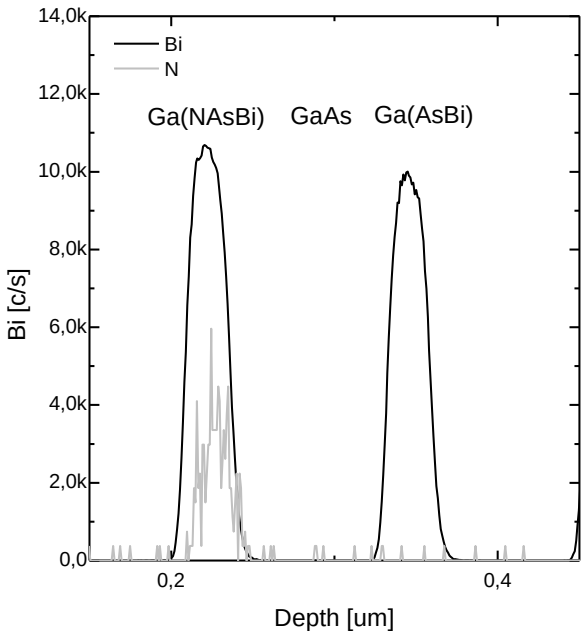


Figure 13: SIMS analysis of Ga(NAsBi) and Ga(AsBi) layers grown at 400°C

Figure 14 shows the results of composition determination for Ga(NAsBi) samples grown at 400 and 450 °C, respectively . There is a linear relationship between the UDMHy (N precursor) partial pressure and the N content of the samples. The N content also increases when the Bi content decreases for a given UDMHy partial pressure. This may be understood in that the Bi and N compete for group V lattice sites, so decreasing the Bi content allows more N to incorporate, and perhaps also that decreased Bi surface coverage during the growth allows more N to reach the growth surface.

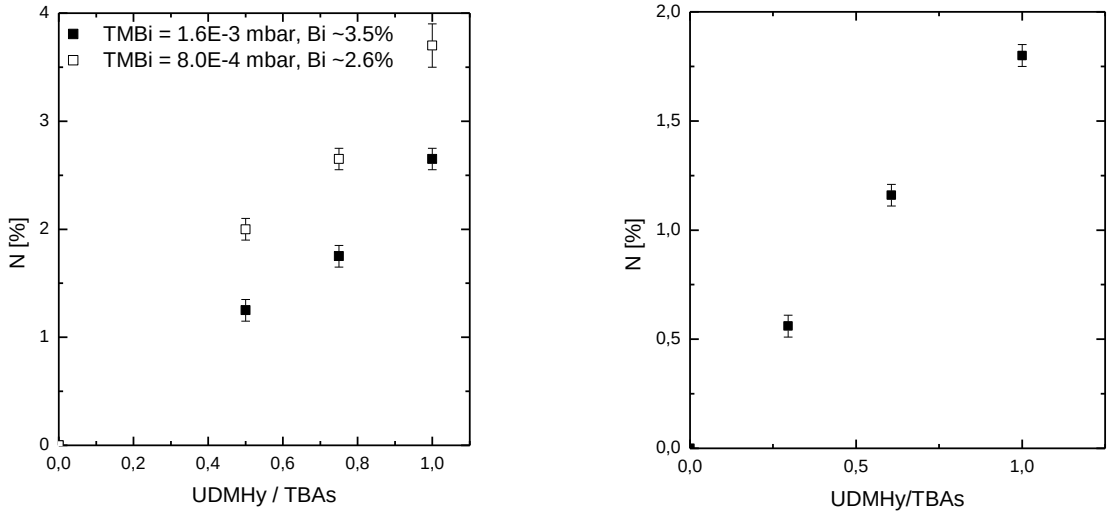


Figure 14: Dependence of N content of Ga(NAsBi) on UDMHy partial pressure for samples grown at 400°C (left) and 450°C (right).

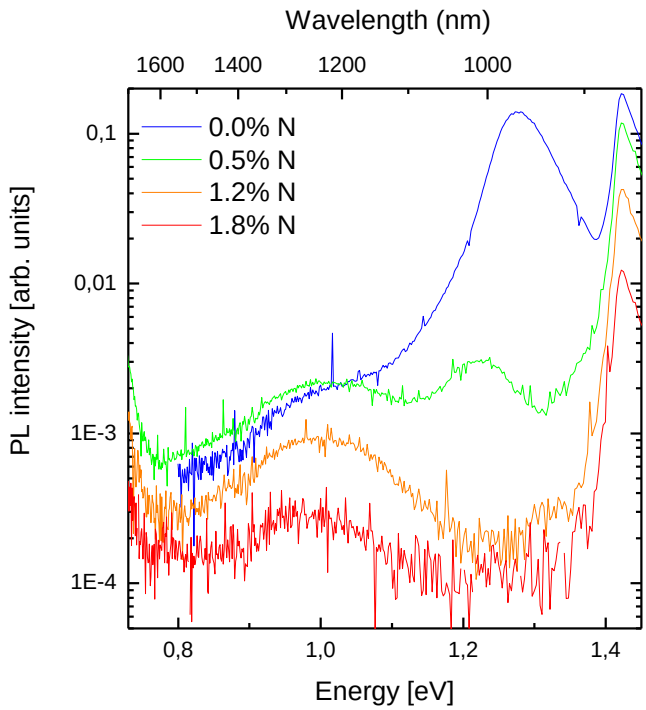


Figure 15: Room temperature PL spectra of Ga(NAsBi) samples grown at 450°C.

Room temperature PL measurements were performed and the spectra are shown in Figure 15. There is a clear redshift in the PL peak from 1.27 eV for the Ga(AsBi) sample to 1.22 eV for the Ga(NAsBi) sample with lowest N content of 0.5%, which is in reasonable agreement with theory. The peak intensity decreases significantly with the addition of N, which is also usually observed in other N containing materials. All spectra have a broad peak at ~1 eV, which is thought to be related

to a defect. It is also interesting to note that the PL intensity from the N-free sample is an order of magnitude greater than for previous Ga(AsBi) samples with similar Bi content grown at 400°C. This suggests that there is an improvement in material quality at the higher growth temperature.

2.5 Theory of the electronic structure of dilute bismide alloys: Tight-binding and k.p models and their application

Despite substantial progress in the growth and characterisation of dilute bismides, there have been comparatively few theoretical investigations of this novel material system. Most previous studies in the literature use density functional theory to investigate the electronic structure[21]. Although such studies can provide a useful understanding of general properties they are not suitable to calculate details of the impact of alloy disorder on the electronic structure, nor are they suited for calculation of expected device properties. To address these two issues, we first developed in BIANCHO an sp^3s^* empirical tight-binding model suitable to calculate the band structure of disordered GaAsBi large supercell structures. Based on the results of this empirical tight-binding model, we were then able to developed a modified **k.p** model which we used to undertake the first investigations of the electronic structure and gain and loss mechanisms in Ga(In)NAsBi bulk and quantum well devices.

We overview here some of the key results from our theoretical work on the electronic and optical properties of dilute bismide and bismide-nitride alloys. We present the tight-binding and **k.p** models for the electronic structure of (In)$GaBi_xAs_{1-x}$. We show that the strong reduction of the band gap (E_g) and increase in the spin-orbit-splitting energy (Δ_{SO}) are explained in terms of a band-anticrossing interaction between the extended states of the host matrix valence band edge and Bi-related resonant impurity states lying in the valence band. Our results, which are in good agreement with the available experimental data, serve to elucidate the origins of the novel electronic properties of dilute bismide alloys and confirm the crossover to an $E_g < \Delta_{SO}$ regime in $GaBi_xAs_{1-x}$ for x ~ 10%, the condition which should lead to suppressed Auger recombination in long wavelength devices. The dilute bismide **k.p** model is applied to calculate the effect of Bi incorporation on the band structure and optical gain of dilute bismide quantum well structures. These calculations contributed to the development of an optimised 2.2% GaAsBi QW laser, and also provided guidance for the development of GaAsBi QW lasers with higher Bi composition (x ~ 7%). General trends relevant to laser operation are also described. Finally, we have also extended our models to the quaternary dilute bismide-nitride alloy $GaBi_xN_yAs_{1-x-y}$ and show how co-alloying of Bi and N offers broad scope for band structure engineering which should lead to the realisation of highly efficient GaAs-based long wavelength photonic devices.

2.5.1 Tight-binding model for electronic structure of GaAsBi and GaNAsBi

We developed an atomistic, nearest-neighbor sp^3s^* tight-binding Hamiltonian to investigate the electronic structure of dilute bismide alloys of GaP and GaAs[22]. Using this model, we could show explicitly that the incorporation of dilute concentrations of Bi in GaP introduces Bi-related defect states in the band gap, which interact with the host matrix valence band edge via a Bi-composition-dependent band anticrossing (BAC) interaction. By extending the analysis to $GaBi_xAs_{1-x}$, we demonstrated that the observed strong variation of the band gap (E_g) and spin-orbit-splitting energy (Δ_{SO}) with Bi composition can be well explained in terms of a BAC interaction between the extended states of the GaAs valence band edge and highly localized Bi-related defect states lying in the valence band, with the change in E_g also having a significant contribution from a conventional alloy reduction in the conduction-band-edge energy. Figure 16 shows that our calculated values of E_g and Δ_{SO} are in excellent agreement with experiment throughout the full investigated composition range ($x \leq 13\%$). In particular, our calculations reproduced the experimentally observed crossover to an $E_g < \Delta_{SO}$ regime at approximately 10.5% Bi composition in bulk $GaBi_xAs_{1-x}$.

[21] A. Janotti, S.-H. Wei, and S. B. Zhang, Phys. Rev. B 65, 115203 (2002)

[22] M. Usman, C.A. Broderick, A. Lindsay and E.P. O'Reilly, Phys. Rev. B 84, 245202 (2011)

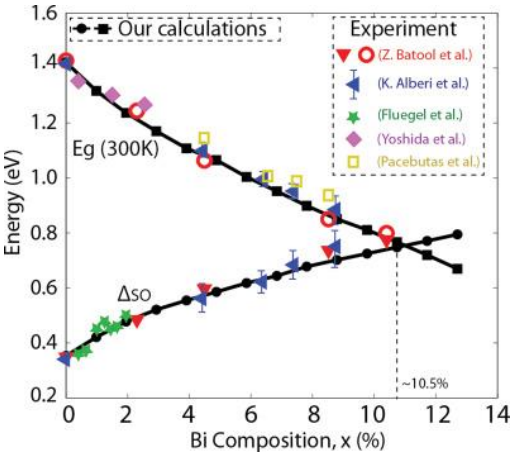


Fig. 16 Calculated and measured variation of the energy gap, E_g and of the spin-orbit splitting energy, Δ_{SO} in bulk $GaAs_{1-x}Bi_x$ structures.

In order to test out the model, we theoretically investigated the electronic structure of experimentally grown $GaBi_xAs_{1-x}$ samples on (100) GaAs substrates by directly comparing our data with room temperature photomodulated reflectance (PR) measurements[23]. Our atomistic theoretical calculations, in agreement with the PR measurements, confirmed that E_g is equal to Δ_{SO} for $x \approx 9\%$. We then theoretically probed the inhomogeneous broadening of the interband transition energies as a function of the alloy disorder. A large broadening of the interband transitions is observed experimentally in PR and photovoltage measurements of dilute bismide alloys. The question then arises as to whether such fluctuations arise e.g. from composition fluctuations throughout the sample or whether they are an intrinsic feature of the electronic structure of $GaBi_xAs_{1-x}$. We showed that it is an intrinsic feature, associated with random fluctuations in local composition. The behaviour of the heavy-hole transitions could be well described using a valence band-anticrossing model. We showed that for the samples containing Higher Bi composition (8.5% and 10.4%), the difficulty in identifying a clear light-hole-related transition energy from the measured PR data is due to the significant broadening of the host matrix light-hole states as a result of the presence of a large number of Bi resonant states in the same energy range and disorder in the alloy. This result was further confirmed by later calculations[24], with both sets of calculations also showing that the band edge inhomogeneous broadening was largely independent of Bi composition over the full composition range considered. This latter result is important for future laser design, indicating that the inhomogeneous broadening at high Bi composition ($x > 10\%$) should be no worse than that which is present in existing dilute bismide lasers. Our calculations also supported a type-I band alignment at the $GaBi_xAs_{1-x}$/GaAs interface, consistent with initial experimental findings[25].

A further test of the model was provided through a joint experimental and theoretical investigation of the electron g-factor in $GaBi_xAs_{1-x}$ epilayers grown pseudomorphically on GaAs, with Bi compositions up to $x = 3.8\%$[26]. We demonstrated that the magnitude of g* increases strongly with increasing Bi composition x. Fig. 17 shows excellent agreement between the theoretical and experimental values of $g^*_{\perp}$ undertaken in the Voigt configuration (magnetic field B in the plane of the QW). There were larger uncertainties in the measurement of $g^*_{//}$, but, given the uncertainties, good agreement was also obtained between theory and experiment for $g^*_{//}$.

[23] Muhammad Usman, Christopher A. Broderick, Zahida Batool, Konstanze Hild, Thomas J. C. Hosea, Stephen J. Sweeney, and Eoin P. O'Reilly, Phys. Rev. B 87, 115104 (2013)

[24] Muhammad Usman and E.P. O'Reilly, Appl. Phys. Lett. **104** (7), 071103 (2014)

[25] N. Hossain, I. P. Marko, S. R. Jin, K. Hild, S. J. Sweeney, R. B. Lewis, D. A. Beaton, T. Tiedje, "Recombination mechanisms and band alignment of GaBiAs/GaAs LEDs", Appl. Phys. Lett.,**100**, 051105 (2012).

[26] Christopher A. Broderick, Simone Mazzucato, Hélène Carrère, Thierry Amand, Hejer Makhloufi, Alexandre Arnoult, Chantal Fontaine, Omer Donmez, Ayşe Erol, Muhammad Usman, Eoin P. O'Reilly and Xavier Marie Phys. Rev. B **90**, 195301 (2014)

The close agreement between the theoretical and experimental data confirms the validity of the theoretical model that we developed and shows that the unexpectedly large variation in g* with composition is due to Bi-induced hybridization of valence states due to alloy disorder, which strongly perturbs the electronic structure.

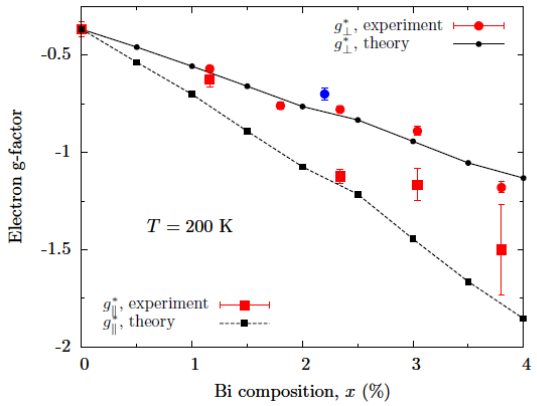


Fig. 17 Calculated and measured variation of electron g-factor components $g^*_\perp$ and $g^*_{//}$ in $GaAs_{1-x}Bi_x$ epilayers grown pseudomorphically on GaAs

In addition to this, we also developed sp^3s^* tight-binding models to investigate the general band structure properties of the dilute bismide-nitride material GaBiNAs, which contains both bismuth and nitrogen. We showed that the effects of N and of Bi are largely independent of each other in random $GaBi_xN_yAs_{1-x-y}$ alloys. This provided the basis to develop a **k.p** model for this quaternary alloy, suitable for the analysis of the wide potential of this quaternary alloy system to produce materials and devices which are close to lattice-matched to GaAs substrates and cover a wide range of optical band gaps, ranging from that of GaAs (~ 870 nm) right through to the mid-infrared (~ 3500 - 4000 nm).

2.5.2 k.p model for electronic structure of GaAsBi and GaNAsBi

Using the sp^3s* tight-binding (TB) model we demonstrated how the observed strong bowing of the band gap and spin-orbit-splitting with increasing Bi composition in $GaBi_xAs_{1-x}$ can be described in terms of a band-anticrossing interaction between the extended states of the GaAs valence band edge (VBE) and highly localized Bi-related resonant states lying below the GaAs VBE. This allowed us to derive a 12-band **k.p** Hamiltonian to describe the band structure of $GaBi_xAs_{1-x}$, made up of the 8 bands used in the conventional **k.p** approach, plus a further 4 bands associated with the localised resonant Bi states[27]. The results of the 12-band model are in excellent agreement with full TB calculations of the band structure in the vicinity of the band edges, as well as with experimental measurements of the band gap and spin-orbit-splitting across a large composition range. Based on a TB model of $GaBi_xN_yAs_{1-x-y}$ we had seen that to a good approximation N and Bi act independently of one another in disordered $GaBi_xN_yAs_{1-x-y}$ alloys, indicating that a simple description of the band structure is possible. We presented a 14-band **k.p** Hamiltonian for ordered $GaBi_xN_yAs_{1-x-y}$ crystals

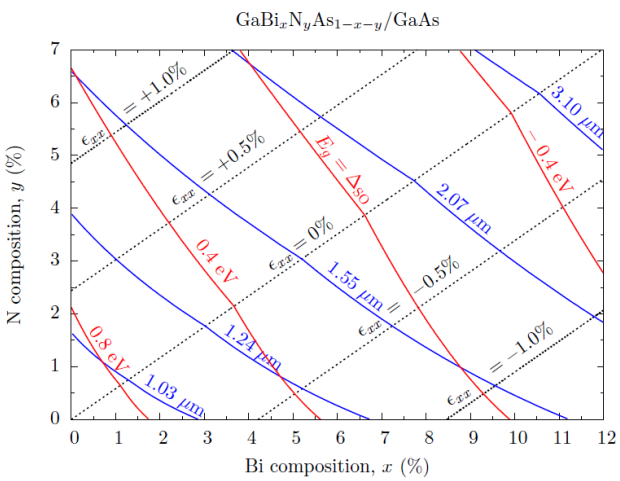


Fig. 18: Calculated variation of energy gap and of spin-orbit splitting energy as a function of N and of Bi composition in GaNAsBi epilayers grown pseudomorphically on GaAs

[27] C.A. Broderick, M. Usman and E.P. O'Reilly, Semicond. Sci. Technol. **28** 125025 (2013)

which reproduced accurately the essential features of full TB calculations of the band structure in the vicinity of the band edges.

The **k.p** models that we derived are therefore ideally suited to the simulation of the optoelectronic properties of these novel III–V semiconductor alloys. Figure 18 shows as example the calculated variation of the energy gap E_g and of E_g - Δ_{SO} for $GaBi_xN_yAs_{1-x-y}$ epilayers grown pseudomorphically on GaAs. We see that by co-alloying Bi and N the $E_g < \Delta_{SO}$ band structure condition can be obtained on GaAs at 1.55 μm and longer wavelengths, clearly demonstrating the potential of $GaBi_xAs_{1-x}$ and $GaBi_xN_yAs_{1-x-y}$ alloys for the design of highly efficient GaAs-based optoelectronic devices with reduced Auger losses across a wide wavelength range. Initial growth of $GaBi_xN_yAs_{1-x-y}$ alloys was undertaken by Marburg, with the measured energy gaps and alloy parameters well described by the theoretical data presented in Figure 18.

2.5.3 Design and Analysis of Bismide-Based Laser Structures

The 12- and 14-band **k.p** models were used both to support the development and optimisation of experimental devices, and also to provide guidance regarding future devices. We used self-consistent gain calculations and the band structure models to explore and optimise the properties of quantum well (QW) laser structures based on both GaAs and InP substrates. Our calculations included input from experimental work undertaken in BIANCHO and by others. We investigated each of the following:

- Design and optimisation of $GaBi_xAs_{1-x}$/(Al)GaAs laser structures with x ~ 2%; the first electrically driven devices demonstrated by BIANCHO
- $GaBi_xAs_{1-x}$/(Al)GaAs laser structures with x ~ 6%; the intermediate target device in BIANCHO
- $GaBi_xAs_{1-x}$/GaAs laser structures with x ~ 14%; the ultimate target device in BIANCHO
- $GaBi_xN_yAs_{1-x-y}$/GaAs laser structures to investigate the impact on gain of combined bismuth and nitrogen incorporation
- $In_yGa_{1-y}Bi_xAs_{1-x}$ quantum wells grown on InP, to investigate the expected gain characteristics and to guide the growth of initial InP-based devices within BIANCHO.

We considered $GaBi_xAs_{1-x}$/AlGaAs single quantum well (SQW) lasers with ***low bismuth composition (x ~ 2%)***, as grown by MOVPE at PUM. We varied both the QW structure and the barrier composition in order to optimise the device design to obtain peak modal gain at a given bismuth composition in the QW. We identified that it was necessary to use GaAlAs barrier layers for low Bi content $GaBi_xAs_{1-x}$ because of the low conduction band offset between $GaBi_xAs_{1-x}$ and GaAs. The results of this theoretical optimisation were communicated to PUM, enabling the growth of a theoretically optimised device design. The use of this design reduced the threshold current of $GaBi_xAs_{1-x}$/AlGaAs lasers (x ~ 2%) by close to a factor of two compared to the initial laser structures.

We also addressed the design of $GaBi_xAs_{1-x}$/AlGaAs SQW lasers with ***intermediate bismuth composition (x ~ 6%)*** in the QW and again theoretically optimised both the QW and waveguide in order to obtain peak modal gain from the device structure. We identified that it was not necessary to include Al in the barrier layers for x >~5%, because there was a sufficient conduction band offset between GaBiAs and GaAs by this Bi composition to allow for good electrical confinement of electrons and holes. This analysis provided critical guidance for the growth of device structures with this intermediate composition, where growth was being undertaken using a hybrid growth approach, with cladding layers grown by MOVPE in Marburg and the active region by MBE at FTMC in Vilnius. The use of GaAs barrier layers allowed for the transfer of structures with Al-free capping layers between the two laboratories, thereby eliminating potential problems associated with defects and oxidation of Al-containing capping layers.

Gain calculations were also undertaken for a $GaBi_xAs_{1-x}$/GaAs laser structure with ***high bismuth composition (x~ 14%)*** - chosen to give peak gain at 1550 nm and for which the spin-orbit-splitting (Δ_{SO}) is larger than the band gap (E_g), to suppress the dominant Auger recombination pathway. We showed that the material gain at this composition is significantly higher than that at

lower x due to the combined effects of larger conduction band offset and strain in the QW. Furthermore, the increased conduction band offset again removed the need to incorporate aluminium in the barrier layers, which preserves the refractive index step between the active region and the cladding, improving the optical confinement in the device.

We also considered the ***quaternary bismide-nitride*** $GaBi_xN_yAs_{1-x-y}$/GaAs material system and showed how this also opens up an alternative route to achieving good material gain at 1550 nm (also with $\Delta_{SO} > E_g$), with nitrogen providing (i) a further reduction of the band gap, meaning that a lower bismuth composition is required, and (ii) partial compensation of the compressive strain in the QW, meaning that QWs with 1500 nm band gap can be grown to greater thicknesses.

Finally, we considered ***InP-based quaternary*** $In_{0.53}Ga_{0.47}Bi_xAs_{1-x}$ SQW laser structures at ***low bismuth composition (x ~ 2%)***. Such structures are suitable as a first step towards growth of Bi-containing lasers on InP with $\Delta_{SO} > E_g$. InP-based lasers with $\Delta_{SO} > E_g$ can be obtained for x >~4% Bi, with emission wavelength >~2.5 μm. We considered the effects of bismuth on the electronic and optical properties of the lasers as we varied the barrier and waveguide structure for a fixed $In_yGa_{1-y}Bi_xAs_{1-x}$ QW and compared the gain characteristics to those of bismuth-free structures with the same band gap, in order to understand the effects of bismuth incorporation on the device properties. Based on these calculations we identified designs suitable for growth for initial demonstration of Bi-containing InP-based laser structures.

Overall the device calculations undertaken to model bismide and nitride based materials and devices fed directly back into the ongoing device design and growth occurring within BIANCHO as a whole, and had a significant impact on the devices grown and demonstrated within the project. The calculations went beyond the current generation of devices, to guide future growth both of $GaBi_xAs_{1-x}$/AlGaAs lasers with higher bismuth compositions, and also growth using alternative strategies, including N incorporation, and growth on InP substrates.

2.6 Device Physics and Engineering

2.6.1 GaAsBi/(Al)GaAs laser structures grown by MOVPE

GaAsBi/(Al)GaAs lasers with different Bi compositions in the active region have been grown by MOVPE at Marburg. For device modelling, the calculations of E_g and Δ_{SO} were based on recent experimental and theoretical data of GaAsBi on GaAs using the valence band anti-crossing model (VBAC) including the effects of strain[28]. The band alignment and the energy states of electrons, heavy and light holes of GaAsBi/(Al)GaAs quantum well structures were determined using Nextnano software with parameters taken from experimental studies on bulk layers[17].

Adding Bi to GaAs mainly affects the valence band. Hence, to improve electron confinement AlGaAs barriers were used in samples with lower Bi composition. Higher Al fraction in the barriers improves the electron confinement. However, the addition of Al in the GaAs waveguide layers reduces the optical confinement factor. Based on preliminary calculations of the optical confinement factor of AlGaAs barriers with 12% and 20% Al were chosen. The quantum well width was selected to minimize the effects of inhomogeneity while maintaining suitable sub-band splitting. The typical laser structure and calculated band alignment diagram is shown in Fig. 19. The structural details of the active region of the investigated laser diodes, calculated band offsets in the conduction (ΔE_c) and valence (ΔE_v) bands, transition energy (E_{e1-hh1}) at room temperature (RT) are summarised in Table 1. The experimentally measured lasing wavelength (λ) and threshold current density (J_{th}) for these devices are also given in the table.

The samples 17152, 17272, 17393 and 17392 had the same 6.4nm quantum well(s) containing 2.2% Bi. The only difference between them is the composition of Al in the waveguide/barrier layers. It can be seen from Table 1 that there is a significant difference in the performance of these device with the lowest J_{th} of ~1 kA/cm^2 being measured in the SQW laser with 12% Al in the waveguide (sample 17273). Fig. 20 demonstrates a comparison of light-current

[28] C. A. Broderick, M. Usman and E. P. O'Reilly, "12-band k.p models for dilute bismide alloys of (In)GaAs derived from supercell calculations",Phys. Stat. Sol. (b), **250**, 773 (2013).

characteristics of these devices at RT and the temperature dependencies of the lasing photon energy. RT lasing was observed in all of the devices containing 2.2% Bi. The RT light versus current characteristics of these devices is shown in Fig 20 (a). The insert in Fig. 20 (b) shows lasing spectra at RT measured at 10% above the threshold. The conduction band offset (from e_1-barrier) in sample 17392 with GaAs barriers is relatively small (~37 meV) and close to the thermal energy of carriers at RT. This results in a high threshold current density of 7.5 kA/cm^2. Furthermore, in addition to the lasing peak from the quantum well at ~938 nm, for temperatures >250K as evident in the inset of Fig. 20 (b), we observe emission from the barrier layers around 897nm consistent with carrier leakage due to the low conduction band offset. The relatively broad lasing spectrum in this device at RT consists of a multitude of Fabry-Perot modes, which indicates a broadened gain spectrum.

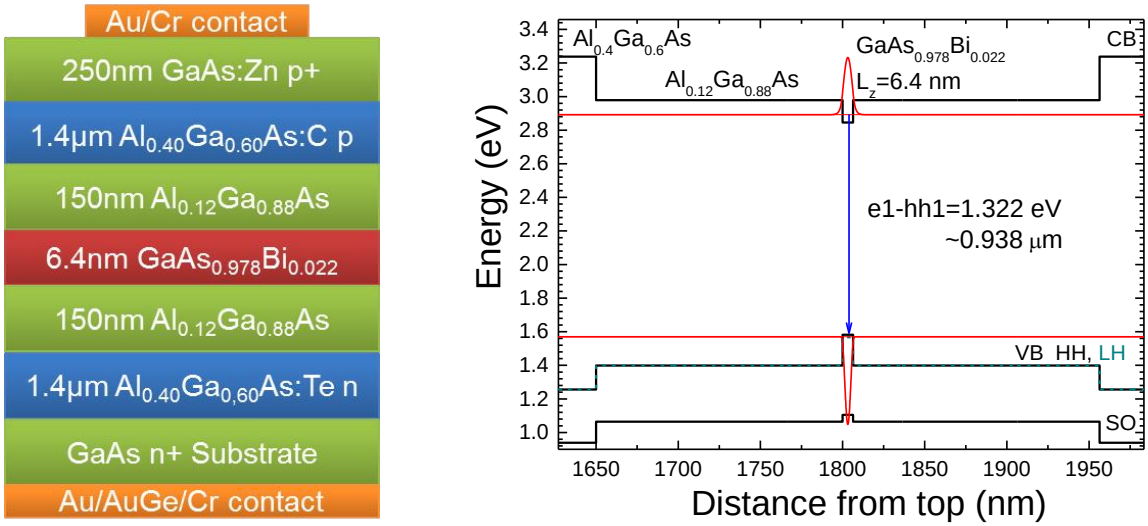


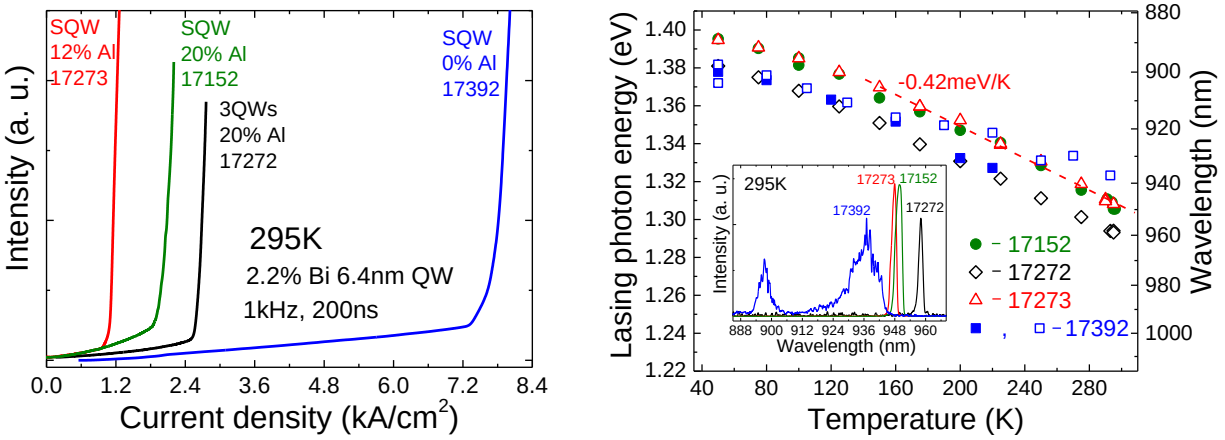
Fig. 19. Layer sequence diagram and calculated band alignment (CB – conduction band, VB – valence band, SO – spin-orbit split off subband) of the active region of the SQW laser structure with 2.2% Bi in a 6.4 nm QW with AlGaAs barriers containing 12% Al (sample 17273).

Table 1. Active region details of the different structures investigated with calculated band offsets in the conduction (ΔE_c) and valence (ΔE_v) bands, transition energy ($E_{e1\text{-}hh1}$) at RT as well as experimentally measured lasing wavelength (λ) and threshold current density (J_{th}) for these devices.

Sample	N_{QW}	QW width, nm	Bi %	Al% in AlGaAs barriers	$E_{e1\text{-}hh1}$, eV (λ, nm)	ΔE_c, meV	ΔE_v, meV	Measured λ, nm	RT J_{th}, kA/cm^2
17152	1	6.4	2.2	20	1.330 (932)	202	225	947	1.5-1.6
17272	3	6.4	2.2	20	1.330 (932)	202	225	958	2.4-2.7
17273	1	6.4	2.2	12	1.322 (938)	133	184	947	1.0-1.1
17392	1	6.4	2.2	0	1.298 (955)	37	123	938	7.5
17393	1	8	4.4	0	1.181 (1050)	73	206	1039 at 180K	4.5 at 180K

To reduce carrier escape into the barrier layers, Al was introduced into the barrier/waveguide layers to increase the band offset. However, a consequence of increasing the Al content of the waveguide has the negative effect of reducing the refractive index contrast between the waveguide region and the AlGaAs cladding layers leading to a reduced optical confinement factor and corresponding

decrease in modal gain. To optimise the device performance, one should therefore take into account two opposite effects related to the composition of Al in the waveguide and barrier layers. We estimated one would expect the 12% Al barrier/waveguide structure to provide >35% improvement in modal gain compared with the 20% Al barrier/waveguide structure[29]. The effect of this on device performance is evident from Fig. 20 (a) and Table 1 where we find that the 12% Al-containing barrier/waveguide devices (sample 17273) have a RT J_{th} of 1.0-1.1 kAcm^{-2} compared with the 20% Al-containing barrier/waveguide devices (sample 17152) which have a substantially higher RT J_{th} of 1.5-1.6 kAcm^{-2}. Thus, in spite of the better electrical confinement of carriers in the SQW device with 20% Al in the waveguide (sample 17152) compared to the corresponding 12% Al sample (sample 17273), the better optical confinement in the latter device resulted in an approximately 50% decrease in the RT J_{th}. However, as evidenced from sample 17392 with a GaAs barrier/waveguide, the higher optical confinement factor cannot compensate for the very low electron confinement. These results clearly demonstrate the need to carefully design the barrier/waveguide structure in QW lasers with low Bi content.



(a) (b)

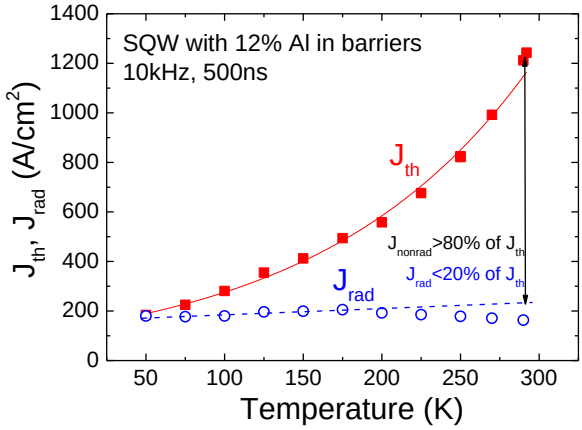
Fig. 20. (a) Light-current characteristics at T=295 K and (b) temperature dependence of the lasing photon energy of 2.2% Bi 6.4 nm SQW and 3QWs lasers with different Al composition in the waveguide/barrier layers (see details in Table 1 for the samples 17152, 17272, 17273, 17392). Solid and open squares in (b) correspond to 17392 devices with 100 µm and 50 µm stripes, respectively.

From Table 1, we also note that the measured lasing wavelength of the devices agrees well with our band-anti-crossing modelling calculations. The small deviation may be caused by many-body effects (band filling and band gap renormalisation) under high carrier injection and non-idealities in the sample growth. The different devices also exhibited a broadly similar temperature dependence of the lasing photon energy with a gradient of -0.42 meV/K which is close to that for standard GaAs-based devices.

For all of the devices, whilst these results are promising, it is important to understand the origin of the relatively high J_{th} values and the extent to which J_{th} is temperature sensitive. To analyse the temperature-dependent performance and to identify the fundamental processes responsible for the relatively high J_{th} values, direct measurements of pure spontaneous emission through a small circular window in the substrate contact (100 µm in diameter) were used to analyse the temperature dependence of the radiative component (J_{rad}) of J_{th}. J_{rad} was determined as the integrated spontaneous emission at J_{th}, which is proportional to the radiative recombination rate. Fig. 21 (a) shows that even in the best laser structure (sample 17273) the main contribution to the threshold

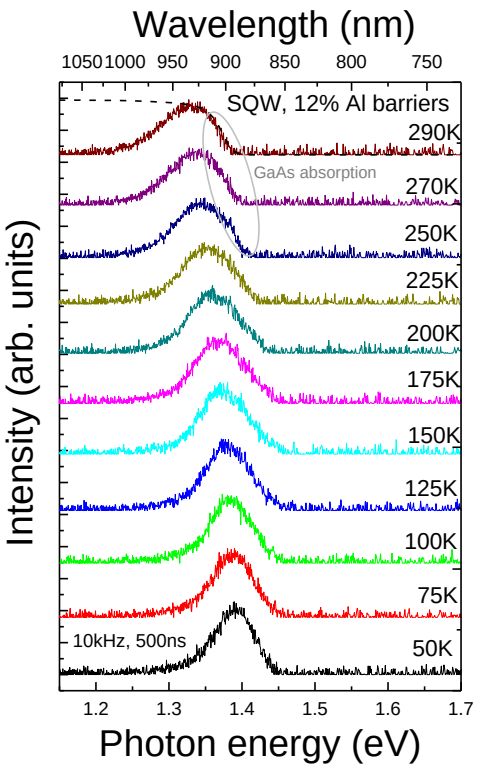
[29] I. P. Marko, P. Ludewig, Z. L. Bushell, S. R. Jin, K. Hild, Z. Batool, S. Reinhard, L. Nattermann, W. Stolz, K. Volz, S. J. Sweeney "Physical properties and optimization of GaBiAs/(Al)GaAs based near-infrared laser diodes grown by MOVPE with up to 4.4% Bi", J. Phys. D: Appl. Phys., **47**, 345103 (2014).

current is due to a non-radiative recombination process. Both structures A and C showed a very similar temperature dependence of J_{th} with a characteristic temperature ($T_0=(d\ln J_{th}/dT)^{-1}$) of ~130 K below 300 K and T_0~100 K at 300-350 K. In Fig. 21 (a) J_{rad} was normalized to J_{th} at the lowest temperature where non-radiative/loss processes are expected to be minimised. For T>200 K, an anomalous decrease of J_{rad} at threshold is observed because of the increasing absorption of the spontaneous emission by the GaAs substrate as shown in Fig. 21(b). At RT the shape of the high energy side of the spontaneous emission spectrum reflects the GaAs-substrate absorption edge, an effect previously seen in 960 nm InAs/GaAs quantum dot lasers[30].From Fig. 21 one can see that $J_{non\text{-}rad}$ accounts for up to 80% of the threshold current at RT[28]. Very similar results were also observed in the sample A with 20% Al in the barriers.



(a)

Fig 21. (a) Temperature dependence of J_{th} and J_{rad} in sample 17273 with the lowest threshold current density at RT. J_{rad} was normalised to J_{th} at 50 K to estimate maximum value of ratio J_{rad}/J_{th} at RT. (b) Spontaneous emission spectra at the threshold. The dashed line presents a transmission spectrum of the GaAs substrate.



(b)

In an ideal laser, the carrier density (and hence spontaneous emission) pins above threshold due to the onset of the fast stimulated emission process and the pinning of the quasi-Fermi levels, which was not observed in the studied devices above J_{th}. A non-pinned carrier density above threshold in the presence of non-radiative losses can further degrade the laser performance by reducing the laser light output and the slope efficiency[31]. A possible explanation of this can be found at very low temperature (20-50 K) and low injected current density (100-150 A/cm^2) where we find that the full width at half maximum (FWHM) of the spontaneous emission spectra (55-65 meV) is >10k_bT indicating a significant inhomogeneous broadening of the carrier distribution.

[30] I. P. Marko, A. D. Andreev, A. R. Adams, R. Krebs, J. P. Reithmaier, A. Forchel, "The Role of Auger Recombination in InAs 1.3 µm Quantum Dot Lasers Investigated Using High Hydrostatic Pressure", IEEE Journal of Selected Topics of Quantum Electronics, **9**, 1300-1307 (2003).

[31] I. P. Marko et al., "Effect of non-pinned carrier density above threshold in InAs quantum dot and quantum dash lasers", IET Optoelectronics, **8**, 88–93 (2014).

To investigate the recombination and loss processes in these devices in more detail we applied high hydrostatic pressure to the devices[32]. From Fig. 21 (a) it is apparent that even in the best 2.2% Bi containing QW devices more than 80% of J_{th} is wasted due to non-radiative recombination. With the application of pressure the band gap increases causing an increase of the lasing photon energy at a rate of 9.7(±0.3) meV/kbar and 10.2(±0.2) meV/kbar in samples 17152 and 17273, respectively, which is close to the pressure dependence of E_g in GaAs (9.8 meV/kbar)[33] and consistent with that previously observed for GaAsBi LEDs[24]. From the pressure data, we determined the pressure dependence of $J_{non\text{-}rad}=J_{th}-J_{rad}$. In both devices $J_{non\text{-}rad}$ has an almost constant pressure dependence, consistent with defect-related recombination dominating the non-radiative path. From the temperature and pressure dependence data, we therefore conclude that defect-related recombination dominates the devices and that further optimisation of the growth of the GaAsBi/AlGaAs active regions is necessary.

Achieving the ultimate goal of Auger recombination suppression requires substantially higher (>12%) Bi fractions in the QW, which therefore needs the development of improved growth at higher Bi fractions. As described elsewhere in this report, samples with an increased Bi composition of 4.4% were grown (sample 17393), the details of which are provided in Table 1. The J_{th} of these devices was substantially higher than the best 2.2% Bi-containing devices resulting in a reduced maximum operating temperature. In this device GaAs barriers were used leading to a relatively small electrical confinement in the conduction band (~73 meV) which can partly explain the high threshold current density of 4.5 $kAcm^{-2}$ at 180 K. Interestingly, the J_{th} for the sample 17393 (4.4% Bi) at 20 K was 1.1 $kAcm^{-2}$ compared with 1.4 $kAcm^{-2}$ for the sample 17392 (2.2% Bi) devices. Thus, in spite of the higher Bi content, at low temperature the 4.4% Bi devices E have a lower threshold current density than the 2.2% Bi 17392 devices. The higher Bi fraction leads to larger band offsets and improved carrier confinement, which at low temperature, offsets the material quality issues associated with the higher Bi fraction. However, the fact that the higher Bi fraction devices have poorer high temperature characteristics suggests that the defect-related recombination may be more important at higher temperatures. This remains the subject of on-going investigations.

2.6.2 Properties of hybrid MOVPE/MBE grown GaAsBi/GaAs based QW lasers

As described earlier, to increase the Bi concentration a combined MOVPE/MBE growth method was used in a three-stage approach. Initially, the lower n-doped 1.4µm-thick $Al_{0.4}Ga_{0.6}As$ cladding and 50nm GaAs waveguide layer were grown by MOVPE at Marburg. The structures then were sent to the Center for Physical Sciences and Technology in Vilnius for MBE growth of the GaAsBi/GaAs single or three quantum well active region, after which they were sent back to Marburg for MOVPE regrowth of the upper GaAs waveguide layer and $Al_{0.4}Ga_{0.6}As$ p-doped cladding.

As discussed earlier, an increased Al fraction in the barriers improves the electron confinement, but at the same time reduces the optical confinement factor. Therefore, in the MBE/MOVPE grown structures with an increased Bi composition studied in this work, as a first step we used GaAs barriers without Al. As an example, for B343 structure with 8nm GaAsBi/GaAs quantum wells containing 6.3% Bi we calculated the conduction band offset (ΔE_c) of 70meV and the valence band offset (ΔE_v) of 260meV and expected transition energy ($E_{e1\text{-}hh1}$) at room temperature (RT) of 1.09eV which corresponds to ~1140nm. The B343 structure with 3QW contained lowest Bi composition in the series of such devices (NB: Bi% was still significantly higher compared to the MOVPE grown structures) and demonstrated the strongest light output and lasing operation. Part of the wafer B343 was processed into broad area 1mm long devices with 50µm and 100µm stripe widths at Marburg. Another part of this wafer was processed at Vilnius into narrower stripe devices of 20µm width. All devices were as-cleaved without any facet coatings.

[32] A. R. Adams, M. Silver, J. Allam, High Pressure in Semiconductor Physics II, Semiconductors and Semimetals, **55**, Academic Press, London 1998

[33] S. H. Wei and A. Zunger, "Predicted band-gap pressure coefficients of all diamond and zinc-blende semiconductors: Chemical trends", Phys. Rev. B, **60**, 5404 (1999).

Lasing in the B343 50µm wide devices was achieved up to 80K with J_{th} of 9.8kA/cm^2 and lasing peak at 1040nm. The device processed in 20 µm stripe exhibited the same J_{th} as the devices with broader stripes but with about 30-40 nm shorter operating wavelength most likely due to variations in the QW uniformity across the wafer. Lasing operation in the narrower devices was achieved up to 300K due to higher current density achievable with the available current source.
Figure 22 (a) shows the spontaneous emission of three different devices (one with 100µm stripe and two with 50µm stripes) measured at a low current density of 100A/cm^2 at a temperature of 22K. Also in this figure we plot the spontaneous emission spectra for a 50µm wide device (marked as 2 in Fig. 22(a)) at higher current densities of 2kA/cm^2 and 3.1kA/cm^{2}as well as a facet emission spectra at 100A/cm^2 and a lasing spectrum measured at 7.5kA/cm^2. Interestingly, despite the fact that the main spontaneous emission peak stays constant (1003nm or 1.236eV) in different devices, the shape of the spectra, especially its longer wavelength side, noticeably varies between the devices. The lasing peak corresponded to 1031nm (1.203eV) on the longer wavelength side of the spontaneous emission spectra. All spectra showed complicated multi-peak shapes with a small feature at high currents corresponding to the GaAs barriers. With increasing current the spectra showed a significant blue shift and broadening due to increased contribution from the higher energy states. The full width at half maximum (FWHM) of spontaneous emission in a 100µm wide device at low current was ~93meV which is almost 50 times greater than kT indicating a large degree of inhomogeneous broadening which could be due to variations of the QW width and Bi composition across the devices. This was also concluded from XRD studies where it was difficult to unambiguously fit the data. Preliminary TEM study showed evidence that the three QWs may have different thicknesses which are smaller than the nominal thickness of 8nm. The FWHM at high current increases almost 2 times compared to the low injection current likely due to the broad inhomogeneous distribution of carriers and band-filling which is normally most pronounced in narrow QWs[34]. However, despite these imperfections, the devices still showed lasing operation demonstrating that by optimising the growth and structure quality the device performance may be significantly improved.

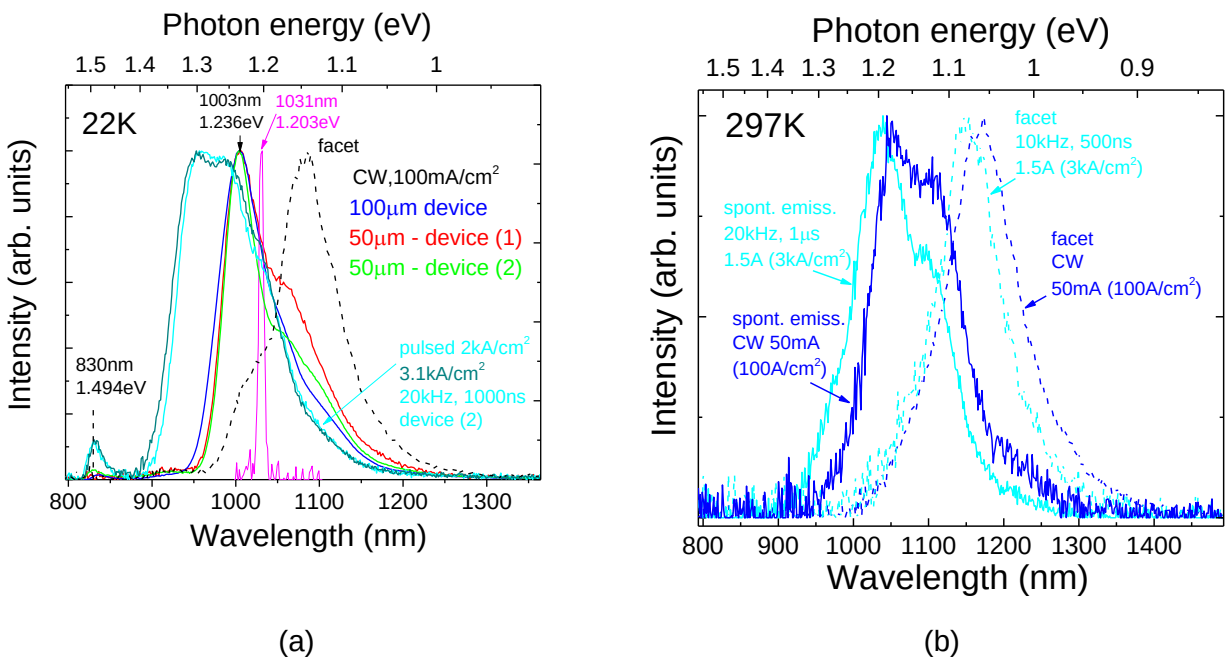


Fig. 22. (a) Spontaneous emission spectra from 3 devices (B343) at T=22K measured at 100A/cm^2 CW current density. A facet emission spectrum (dashed) measured at the same conditions is given for comparison. Spontaneous emission spectra at high current 1000mA and 1550mA (2kA/cm^2 and 3.1kA/cm^2, respectively). and a lasing spectrum measured at 7.5kA/cm^2 are also presented; (b) Spontaneous and facet emission spectra at 297K at low (100A/cm^2) and high (3kA/cm^2) injected current in 50µm wide B343 devices.

[34] P. A. Chen, C. Juang, C. Y. Chang, "Carrier-induced energy shift in GaAs/AlGaAs multiple quantum well laser diodes", IEEE Journal of Quantum Electronics, **29** (10), 2607 (1993).

Figure 22(b) shows comparison of the spontaneous emission and facet emission spectra at low (100A/cm^2) and high (3kA/cm^2) injected current densities. As mentioned above, the facet emission peak is shifted to longer wavelength due to reabsorption effects as the light propagates along the cavity. However, the peak shift is relatively large (>100meV) in this structure. Interestingly, the spontaneous emission spectral width did not show such a strong dependence on injected current as it was observed at 22K (see Fig. 22 (a)). This can be explained by improved thermal carrier redistribution as at higher T carriers have enough kinetic energy to thermalise to lower energy states thereby reducing the effect of inhomogeneous broadening. At low T carrier localization effects are dominant and the emission spectra reflect the component of the carrier distribution function due to inhomogeneous broadening. The main spontaneous emission peak at 100A/cm^2 corresponds to 1055nm. It was also possible to distinguish two smaller peaks at 1105nm and 1220nm. Assuming the nominal QW width of 8nm, the main peak would correspond to 4.4%Bi and the other two peaks would give 5.6% and 7.7% of bismuth, respectively (see below Fig. 25 with calculated dependence of a QW transition wavelength on the QW width for different Bi%). On the other hand, if we assumed a constant Bi composition in all 3 QWs (a single theoretical curve in Fig. 25) it would be difficult to explain the origin of the observed three peaks by variation of the QW width alone. Therefore we believe that inhomogeneity of the active region is caused both by variation of the QW width and Bi composition between the three QWs and also non-uniformity along the cavity. The aforementioned values of the Bi composition could be underestimated if the real QWs widths are smaller. Therefore, to the best of our knowledge these first devices produced by the MBE/MOVPE approach have the largest Bi composition in the QW active region. Also, structural investigations of such structures showed that the quality of the QW structures with large Bi content is significantly poorer than in samples containing less bismuth. This is caused by formation of multiple pit-like structuers which introduce additional defects as well as significant optical losses deteriorating the optical characteristics.

Figure 23(a) presents the facet emission spectra from the B343 laser processed into 20µm wide stripes measured at a low current of 50mA (current density of 250A/cm^2) and lasing spectra at different temperatures. Two facet emission spectra at higher currents at 22K and 295K are also shown with dashed lines. At low temperatures the emission spectra below threshold are broad (~120meV) with several peaks visible at shorter wavelengths as discussed above due to inhomogeneity and carrier localisation effects. One can see a very strong blue shift of the facet emission with increasing current which was measured to be as much as 100meV with increasing current density from 0.1 up to 20kA/cm^2. This value is comparable to the conduction band offset in these devices which indicates that insufficient carrier confinement may be an additional factor limiting the device performance due to carrier leakage (especially at high temperatures). Therefore adding a small amount of Al into the barriers would be expected to improve carrier confinement and the device performance. The observed blue shift of the emission peak at high current and a shorter lasing wavelength suggest that the actual QW width may be smaller than the nominal value of 8nm.
The temperature dependence of the threshold current density in the B343 laser diode is presented in Fig. 23(b). At room temperature J_{th} was very high ~25kA/cm^2 which is 25 times greater than its value in the best single QW devices with 2.2% Bi [28]. Despite a very high value of J_{th}, its temperature variation showed an unusual behaviour which similar to that observed in highly disordered systems like self-assembled quantum dots[35,36,37]. This is normally a result of a

[35] I. P. Marko, A. D. Andreev, A. R. Adams, R. Krebs, J. P. Reithmaier, A. Forchel, "The Role of Auger Recombination in InAs 1.3 µm Quantum Dot Lasers Investigated Using High Hydrostatic Pressure", IEEE Journal of Selected Topics of Quantum Electronics, **9**, 1300-1307 (2003).

[36] I. P. Marko, N. F. Massé, S. J. Sweeney, A. D. Andreev, A. R. Adams, N. Hatori and M. Sugawara, "Carrier transport and recombination in p-doped and intrinsic 1.3 µm InAs/GaAs quantum-dot lasers", *Appl. Phys. Lett.*,**87**, no. 21, 211114 (2005).

[37] M.T. Crowley, I. P. Marko, N. F. Masse, A. D. Andreev, S. Tomic, S. J. Sweeney, E. P. O'Reilly, A. R. Adams, "The importance of recombination via excited states in InAs/GaAs 1.3 µm quantum-dot lasers", IEEE Journal of Selected Topics in Quantum Electronics, **15**(3), 799-807 (2009).

combination of the thermally induced carrier redistribution processes as well as activation of non-radiative recombination or carrier leakage.

To estimate the variation with temperature of the radiative recombination efficiency of these devices we plot in Fig. 23(c) the temperature dependence of the integrated spontaneous emission at a constant current density of 100A/cm^2 (for 50µm and 100µm wide devices). Providing the light collection efficiency remained constant, any variation of the measured integrated intensity would be due to changes in the internal quantum efficiency. As presented in Fig. 23(c), the efficiency showed a relatively strong decrease in the whole temperature range from 20K to 295K indicating the presence of a non-radiative process which would be responsible for the temperature sensitivity of the threshold current density.

Figure 23(d) presents the temperature dependence of FWHM of the spontaneous emission spectra from two different B343 devices at low current density of 100A/cm^2 as well as the FWHM of the spontaneous emission spectra of one of these devices at a high current density of 3kA/cm^2. The FWHM helps to see the effect of inhomogeneous broadening which is responsible for the very large value of the FWHM at low temperature. With increasing temperature this value decreases reaching a minimum around 200K. The fact that at room temperature the FWHM is almost the same at 100A/cm^2 and at 3kA/cm^2 indicates that the inhomogeneous broadening component in the carrier distribution function is still dominant even at 295K. Thus, a non-radiative process coupled with the thermally activated carrier redistribution processes which can be seen from the temperature dependence of the FWHM determine the unusual temperature dependence of the threshold current density in this laser device.

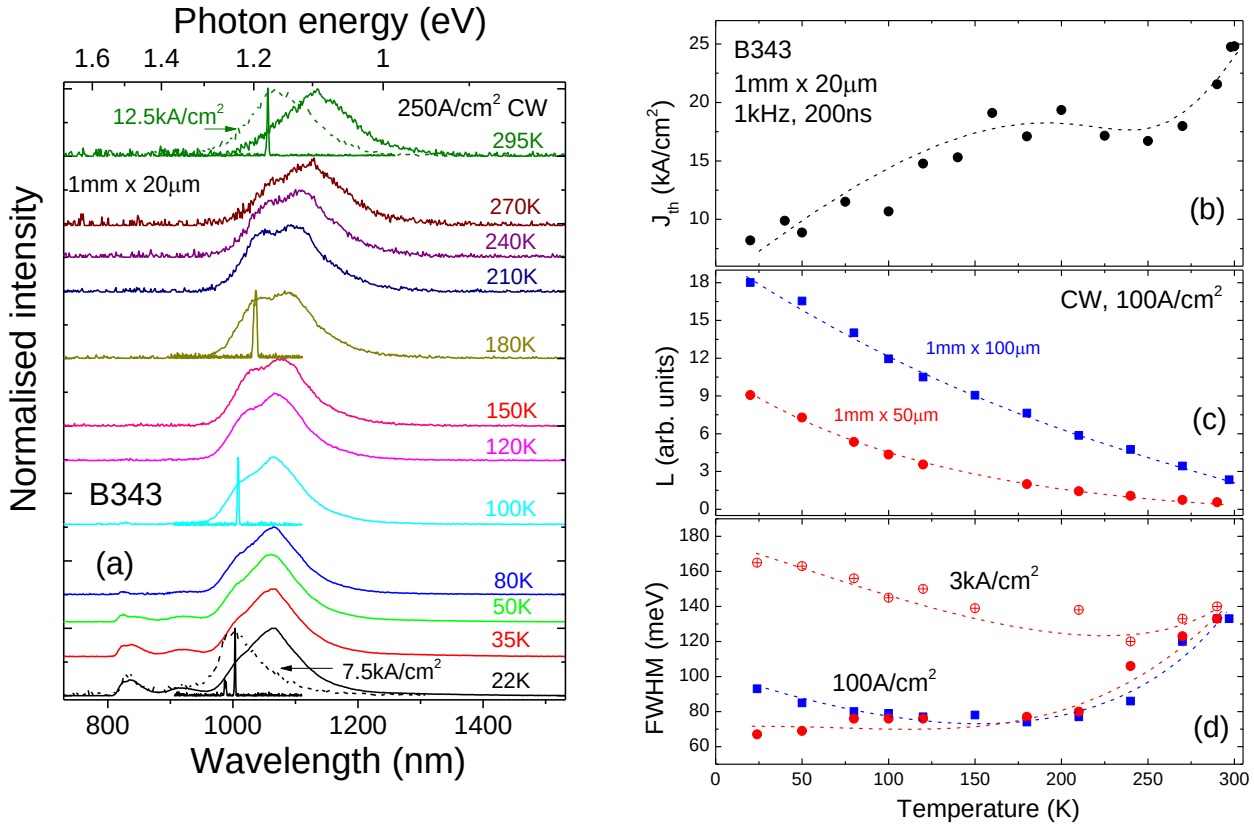


Fig. 23. (a) Facet emission spectra at low CW current (50mA or 250A/cm^2) and lasing spectra of B343 laser at different temperatures. The spectra at higher currents at T=22K and 295K are also shown with dashed lines; (b, c, d) Temperature dependencies of the threshold current density J_{th} in the 20µm wide device, radiative efficiency at constant current and FWHM in 50µm and 100µm wide devices, respectively.

To further help identify the dominant recombination process we carried out a high hydrostatic pressure study[38] of these devices similar to the previous characterisation of 2.2%Bi MOVPE-grown lasers[28]. The observed almost constant pressure dependence of J_{th} indicates dominant recombination process via defects even at 76K as it was observed in the 2.2% Bi devices at room temperature [28]. With increasing temperature this contribution will also increase. This helps explain the relatively constant T_0 value around RT of 100-130K as reported for several devices with different Bi composition[28,39].

To increase Bi composition in QWs and to further shift lasing wavelength towards 1.3-1.5µm range several growth cycles were carried out. Table 2 summarises the details of the MBE-grown section of the different structures. Bi% in Table 2 were obtained from the modelling using experimental electroluminescence (EL) peaks and nominal QW widths, which however may have a considerable uncertainty as discussed before for the B343 laser structure.

Table 2: Summary of MOVPE/MBE hybrid laser structures. Bi % were estimated using experimentally determined QW ground state transition from Fig. 24 and modelling results presented in Fig. 25.

Sample Number	Spontaneous emission peak, eV (nm)	estimated Bi%	QW width, nm	Number of QWs
B343	1.090 (1138)	6.3	8	3
B431	1.029 (1205)	7.1	12	3
B432	0.990 (1253)	8	12	3
B514	1.100 (1127)	5.9	8	5
B521	1.102 (1125)	6.1	8	5
B522	1.029 (1205)	7.6	8	5

For comparison of different structures Fig. 24 shows their spontaneous emission spectra measured under continuous wave (CW) excitation from the substrate window in the B343 device and from the top contact window in the other samples. From the peak positions of these spectra (Fig. 24, assumed to correspond to the QW peak emission) and the calculated variation of the transition energy versus QW width for different Bi concentrations as plotted in Fig. 25, we estimated the Bi concentration for each sample assuming homogeneous QWs with the nominal thickness (see Table 2).

The B343 devices showed the shortest emission wavelength in the studied series but also the strongest light output. Room temperature spectra did not show any evidence of emission from the barriers unlike that observed in the B5xx samples (see Fig. 24). The emission from the barriers in the B431/B432 devices was also very weak. The emission peak in B431, B432 devices as well as in the devices B522 corresponded to wavelengths above 1200nm. From the measured emission peak we estimated the Bi composition in B431 to be about 7.1% and around 7.6% and 8% in the B522 and B432 devices, respectively. However, devices B514, B521, and B522 demonstrated a relatively strong emission from the barriers even at RT, indicating a poor injection efficiency. The light output from these devices was also significantly weaker compared to the B343 and B431 devices. Interestingly, the facet emission from these devices was significantly shifted (~100nm) towards longer wavelengths compared to the spontaneous emission peak suggesting both a significant spectral broadening and a strong reabsorption of the QW emission as it travels along the laser cavity.

[38] I. P. Marko and S. J. Sweeney, "Optical and electronic processes in semiconductor materials for device applications" in book "Excitonic and Photonic Processes in Materials", Editors: Jai Singh and Richard T. Williams, Excitonic and Photonic Processes in Materials, Springer Series in Materials Science, **203**, 253-297 (2015).

[39] T. Fuyuki, K. Yoshida, R. Yoshioka, M. Yoshimoto, "Electrically pumped room-temperature operation of $GaAs_{1-x}Bi_x$ laser diodes with low-temperature dependence of oscillation wavelength", Appl. Phys. Express, **7**, 082101 (2014).

It was observed that devices B521/B522 exhibited an enhancement of light output from the QWs and a reduced emission from the barriers when the temperature was increased from 20K up to 100K, which may indicate the influence of carrier localisation on the emission behaviour. With increasing T, the emission intensity from the GaAs barriers was decreasing whereas at the same time the QW emission intensity was increasing resulting in an increased light output from the QWs of ~30%with increasing T from 20K up to 100K demonstrating the effect of improved quantum efficiency due to a thermally improved carrier injection efficiency. With a further increase in the temperature above 100K the light output from the device decreased due to a stronger contribution of the loss processes.

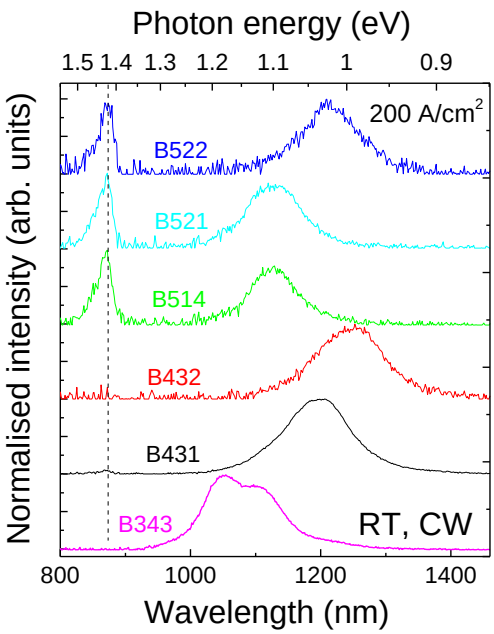


Fig. 24. Electroluminescence (spontaneous emission) spectra measured at 200A/cm^2 from a window in the 50µm wide top contact of the different devices grown using the MOVPE/MBE hybrid growth approach.

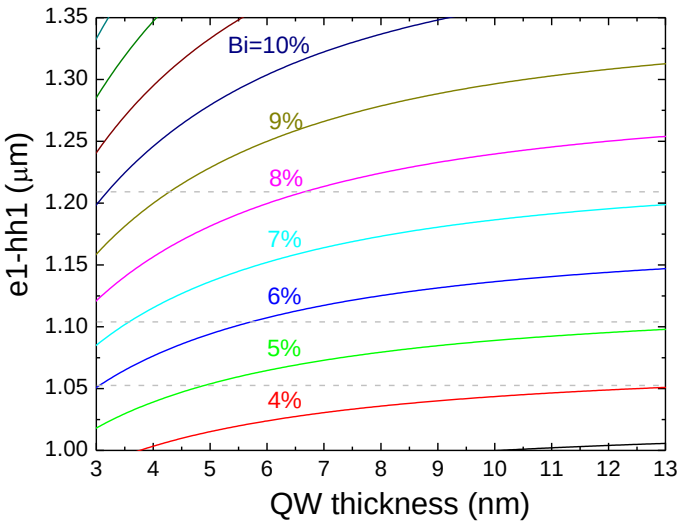


Fig. 25. Calculated variation of the transition wavelength at T=300K versus QW width for different Bi concentration. From this we estimated the Bi percentages in each sample as presented in Table 1. The dashed lines represent several peaks observable in the spontaneous emission from the B343 devices at 100A/cm^2 at room temperature.

To summarise, significant progress has been achieved in understanding the performance of GaAsBi/GaAs lasers with increased Bi concentration. The combined MBE/MOVPE approach has been developed to overcome issues in growing laser structures with ≥5-6%Bi using MOVPE or MBE growth only and has demonstrated electroluminescence beyond 1200nm (structures with up to 8% Bi) and RT lasing operation at 1.06µm in the laser diodes containing around 6% Bi. Using temperature dependent measurements of stimulated and pure spontaneous emission as well as high hydrostatic pressure, we showed that the device performance, particularly the high threshold current density at RT is presently limited by both defect related non-radiative recombination and significant inhomogeneous carrier distribution due to inhomogeneity of the QW. This indicates the need of further growth optimisation and refinement.

3 Potential impact and the main dissemination activities and exploitation of results

3.1. Know-how and Intellectual Property

3.1.1 Know-how and IP within BIANCHO

One of the key pieces of IP underpinning the BIANCHO project, namely the benefits of using bismide alloys to eliminate Auger recombination was filed for patent protection by the University of Surrey, prior to the start of the project.

Considerable know-how was generated by BIANCHO. Substantial progress was made in the growth of dilute bismide lasers, including hybrid growth where the active region was grown by MBE and the barrier and cladding layers by MOVPE, allowing us to extend demonstration of the world's first electrically pumped dilute bismide laser to bismuth compositions as high as 6%. Our overall knowledge and understanding of dilute bismide materials and their potential applications has also increased substantially. We submitted 3 patent applications during the project duration, including the following topics:

- Uni-Travelling-Carrier photodiode with bismide absorber layers (Lithuanian patent#6044 25/06/2014)
- Semiconductor Saturable Absorber Mirror (SESAM) on GaAs substrate with bismide absorber layers (optical bleaching up to the wavelengths of 1600 nm demonstrated experimentally) (Lithuanian patent #6045 25/06/2014)

Overall, the knowledge we have developed has enabled major progress towards the development and demonstration of efficient bismide-based telecom components. Major progress has been made in growth-related know-how, much of which has been presented in the scientific literature. Likewise the understanding that the BIANCHO project developed of the intrinsic material properties and device characteristics have also been presented both in publications and through presentations at relevant conferences.

3.1.2 Know-how and IP external to BIANCHO

The BIANCHO partners were well linked to the wider bismide community, facilitated by our active participation and leadership of the annual International Workshop on Bismuth-Containing Semiconductors. This meeting is now established as the primary meeting for research on dilute bismide semiconductors. The second International Workshop was held in Surrey in July 2011, and the 5th Workshop was hosted by Tyndall from 20-23 July 2014. BIANCHO was well represented at the meeting, including 1 invited talk and BIANCHO partners being co-authors on 10 further presentations. BIANCHO partners had in addition two invited talks at the final meeting of EU COST Action MP0805 "Novel Gain Materials and Devices Based on III-V-N/Bi Compounds" in September 2013.

We have searched but have not find any evidence of dilute bismide patents relevant to BIANCHO published since the start of the project. US Patent No. 8,492,702 "Method and system for detecting light having a light absorbing layer with bandgap modifying atoms" (published July 23 2013) is returned for the search word "bismide". This patent addresses "generation of photocurrent indicative of absorption of photons at any wavelength at least in the range of from about 3 μm to about 5 μm", outside the wavelength range of primary interest to BIANCHO, but indicative of the growing interest in the use of dilute bismide alloys across a range of applications.

The success of the BIANCHO project in demonstrating electrically pumped dilute bismide lasers has spurred international interest in the growth of dilute bismide materials and devices, This includes **large projects funded both in China and in USA**, with Prof. Shumin Wang [Shanghai Institute of Microsystem and Information Technology (CAS)] leading two Chinese-funded bismide-related projects as part of the Thousand Talents programme and with the University of Wisconsin leading a large US project on growth of novel alloys, including dilute bismide alloys.

Laser Devices and Growth: The demonstration of the first electrically pumped dilute bismide laser by the BIANCHO consortium gives us clear world leadership in this field. Based on our success, a number of other groups are now also actively seeking to grow laser structures. These include Yoshimoto's group from Kyoto Institute of Technology, Tom Tiedje in University of Victoria, and University of Wisconsin. The Yoshimoto group have recently reported an electrically pumped bulk GaAsBi laser, containing ~3% Bi in the active region.

Materials:, There is an increasing interest in the growth of dilute bismide alloys, not just on GaAs but across a range of substrates, including InP, GaSb and InAs. Many new groups have entered the field, which have previously made a significant impact on growth of other mis-matched alloys using both MOVPE and MBE. Significant progress has been made in MOVPE growth by the Wisconsin group; while several other groups are making good progress in MBE growth of a wide range of dilute bismide alloys.

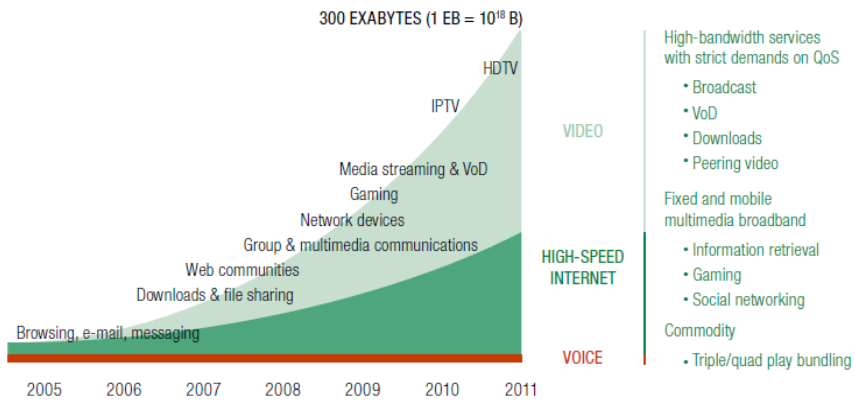
3.2. Prospects for Commercial Exploitation and Wider Impact

BIANCHO targeted to develop temperature-insensitive telecom components, including lasers, semiconductor optical amplifiers (SOAs) and electro-absorption modulators. It also targeted bismide-based components for efficient terahertz generation and detection. There is significant potential for commercial exploitation of such uncooled components both for telecoms applications, and as optoelectronic terahertz frequency range sources for telecoms and wider applications.

To assess this fully, we present in Section 3.2.1 an overview of the current telecommunications market, along with a summary of current and future telecommunications system requirements in Section 3.2.2. The prospects for Bismide-based Telecom components are presented in Section 3.2.3. This is followed by an analysis of optoelectronic THz frequency range components on Section 3.2.4. The BIANCHO Consortium concedes that the results achieved for Bismide-based Telecom components, although world-leading, are nevertheless below the expectations outlined in the Description of Work. Unfortunately, none of the telecom device target specifications have been reached. Section 3.2.3 therefore also includes further discussion of the next steps required before exploitation, as well as a brief discussion of envisaged future funding resources.

Overall, we conclude that there is a significant and growing telecommunications market for these potential products to be sold into, as well as a smaller but important market for THz frequency range components.

3.2.1 Telecommunications Market Size



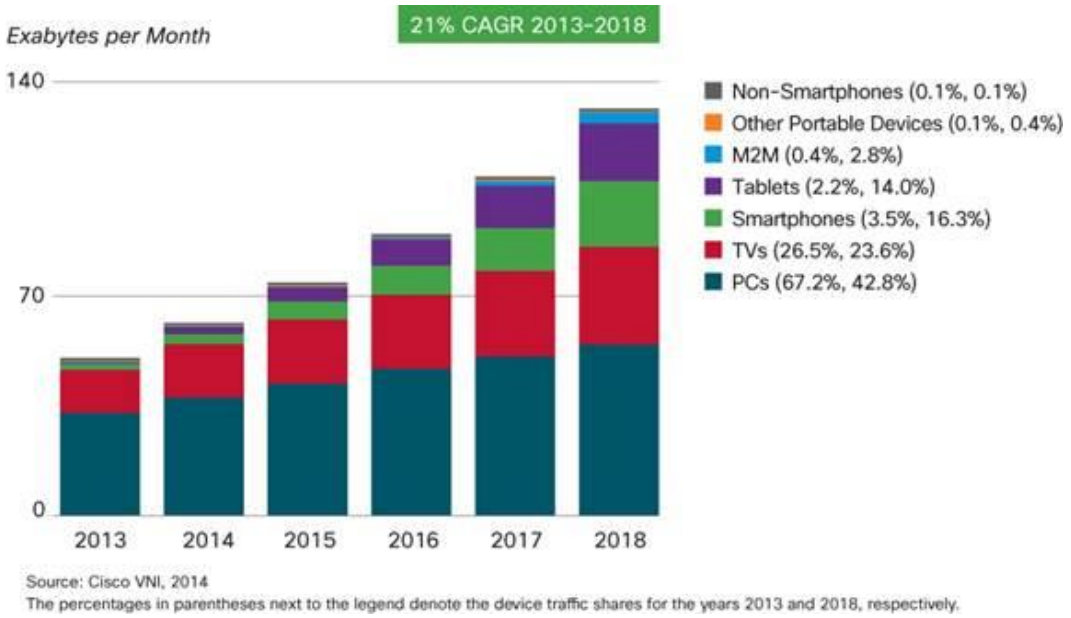


Figure 26: The Explosive Growth in Network Traffic: note that the data in the upper figure is per annum[40] while the data in the lower figure is per month[41]

The telecommunications market has shown astonishing growth over the last 10 years (see Fig. 26). Usage of telecommunications has soared with new technologies and new applications, mobile and fixed, changing the way that people live their lives. Where in 2008 global revenue generated by the telecommunications industry was about $2.9 trillion, in 2013 revenue had grown to $3.87 trillion. By 2017, TIA forecasts global revenue of about $4.58 trillion[42].

3.2.2 Optical Communications Component Market

The global optical communications component market was estimated at €3.1 billion in 2009[43] and at €5.4 billion in 2013[44]. Internet traffic continues to grow rapidly. Global IP traffic has increased more than fivefold in the past 5 years, and is expected to increase threefold over the next 5years[45]. Overall, IP traffic will grow at a compound annual growth rate (CAGR) of 21% from 2013 to 2018. However, revenue for network operators is being squeezed. Consumer expectation is for more bits for the same price as before, which squeezes the network operators' revenues unless they can lower the cost of their operations through simplified networks. This provides a key driver for photonics solutions for communications since photonics can provide the lowest power loss as a function of distance of any transport medium. Future successful companies will operate in countries with a good ICT infrastructure. FTTH is regarded as essential, and the pace of roll-out in Europe has lagged behind both the Far East and the USA.

Over this time period the Internet will continue to be the dominant user of the core network capacity. The growth of new video based internet services is fueling capacity growth matching or exceeding previous rates. However, as there will be a reluctance to install additional core network fibre infrastructure on routes where fibre already exists, the emphasis will be to use existing fibre but with greater spectral efficiency.

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[40] Richard Dorward, Ericsson Broadband Networks, Presentation at Photon '08, 28th August 2008

[41] http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/VNI_Hyperconnectivity_WP.html

[42] http://ipcarrier.blogspot.ie/2014/07/global-telecom-revenue-will-hit-458.html

[43] OIDA Global Optoelectronics Industry Market Report and Forecast 2009

[44] http://www.cablinginstall.com/articles/2014/08/ovum-optical-growth-report.html

[45] http://www.cisco.com/c/en/us/solutions/collateral/service-provider/ip-ngn-ip-next-generation-network/white_paper_c11-481360.html

The growth in internet also brings increasing energy demands on data retrieval, transmission and downloading. A recent study found that transmitting the bytes across the Internet accounts for the bulk of energy usage and emissions when streaming videos[46]. The study considered video streaming in 2011, when Americans streamed 3.2 billion hours of video, which consumed 25 petajoules of energy (enough to power about 175,000 U.S. households for one year) and emitted 1.3 billion kilograms of CO_2.Results from this study indicated that designers and policy makers should focus on the efficiency of end-user devices and network transmission energy to curb future increases in energy use from the proliferation of video streaming and related applications. This highlights the market need for the type of cooler-less components targeted in BIANCHO.

3.2.3 Prospects for Bismide-based Telecom Components

The analysis above highlights the industry requirement for uncooled devices; whether it is to enable innovative architectures such as long-reach WDM; to maintain the current business model of existing deployments where revenue per bit has flat-lined; or simply to reduce the burgeoning need for power that our communications networks demand from our power grids, whilst capacity increases.

Key areas where the types of devices targeted in BIANCHO would bring critical advantage include:

- Data centres increase in size and density bringing increased requirement for reduced power consumption and higher temperature operation.
- New system development is turning to 400G or IT systems. These are driving the requirements for multiwavelength integrated components which currently require tight temperature control through use of thermal electric coolers with poor energy efficiency.
- Reduced equipment footprint is driving towards smaller and smaller components. Heat dissipation and thermal crosstalk become very important. Devices that are more efficient and work at higher temperature are vital.
- In silicon photonics, a wafer-bonded III-V optoelectronic device has to be able to work efficiently at elevated temperature as direct heat-sinking is not available.

In addition, an emerging area where higher temperature operation of optoelectronic devices is also desirable is for systems which operate in hostile environments, such as those needed for microwave antenna remoting. Future 5G networks are likely to place an increased need for a great many high capacity optical links between remote microwave antenna arrays and the centralised base units where signal processing is to be performed.

The inclusion of CIP as a partner within Biancho provided a route for development and exploitation of temperature insensitive components. However, during the project, it became clear that developing processes for growing high quality materials with significant bismuth content was the major challenge. This moved the focus away from devices as the output, towards epitaxy techniques and material analysis. Therefore the detailed knowhow that Marburg and FTMC have developed is a valuable asset and can be exploited either in future research or in licensing to others.

During the project, CIP was acquired by Huawei (now the world's largest telecoms equipment supplier). This was part of Huawei's global strategy to become a vertically integrated company, and recognises the importance of innovative optoelectronic devices as a key part of developing the next generation of telecom systems. Huawei is working to increase its research activity in Europe and is committed to developing optolelectronic chip technology in Europe. It is thus well placed to exploit innovative materials technology in optoelectronic chips.

Prior to the BIANCHO project, research on bismide-based semiconductors had been primarily materials based, with little progress towards device realisation. Overall, our work drove forward the growth and optimisation of dilute bismide alloys, including demonstration of the first electrically pumped dilute bismide lasers, and the first lasers with $x > 6\%$, although not yet Auger-free lasers. The BIANCHO partner, FTMC has taken GaBiAs photodetectors through to commercial application, as detailed in the next section. However, in order to exploit the potential of dilute

[46] ArmanShehabi *et al* 2014 *Environ. Res. Lett.* **9** 054007 doi:10.1088/1748-9326/9/5/054007

bismide alloys for telecom component and wider applications, further progress remains dependent primarily on materials development for device demonstration.

Based on progress in BIANCHO, there are several directions which remain promising for materials and device development. These include:

- The further development of GaAsBi(N)/GaAs alloys for ***efficient near- infrared lasers*** on GaAs, absorbing layers for ***high efficiency solar cells***, and for mid-infrared ***photodetectors***
- The development of InGaAsBi/InP alloys for ***mid-infrared lasers*** and ***photodetectors*** using conventional InP substrates
- The development of InAsBi/InAs materials for applications in advanced, ***high sensitivity mid-infrared photodetectors*** including avalanche photodetectors

All of these routes require significant funding resources. All BIANCHO partners are keen to see further development and exploitation of these alloys. To that end, the partners:

- are continuing to advocate the promises and the corresponding high exploitation potential of bismide-containing III-V compounds by publications, conference contributions and during topical events, including to input through Photonics21
- have disclosed and continue to disclose through publications and presentations relevant technical information on the growth of high-quality bismides in order to help other groups making progress in the field and so to promote the development of lasers (and related devices) with significant Auger recombination suppression
- are separately pursuing national funding opportunities, ranging from individual researcher support to larger-scale proposals
- are supporting relevant individual EU proposals, such as Marie Curie Fellow applications
- will work on making dedicated contributions to enable funding of BIANCHO-related topics in future Calls of the European Commission, in particular under bottom-up disruptive research priorities.

3.2.4 Ultrafast Detectors and THz Generation

As part of the BIANCHO project FTMC undertook the fabrication and investigation of UTC-photodiodes including a GaBiAs absorbing layer. Their analysis showed that the low band offset between GaBiAs and GaAs makes these devices very suitable for use as ultrafast photodetectors for near-IR radiation, and also suitable for use in terahertz generation. Further modelling was also performed at FTMC outside of BIANCHO for device structure optimization. Growth and processing of the optimized structure has been undertaken. These devices demonstrated photosensitivities of 20 mA/W at 1064 nm. This is an order of magnitude larger than that for the initial devices, and comparable with those of p-i-n photodiodes with a bismide absorber layer (Bastiman, Sweeney, 2012). Based on these results and the wider analysis by FTMC, we conclude that dilute bismide UTC photodiodes represent a very promising route towards efficient THz generation. It should be noted that the SME TERAVIL, which is a spin-off company of the FTMC group, is already producing photoconductive THz emitters and detectors based on GaAsBi epitaxial layers as well as whole THz time-domain-spectroscopy systems using these components activated by Yb doped fiber laser pulses (see http://www.teravil.lt/products.php). Research on this topic is continued by FTMC group; recently the group has developed bismide-based photoconductive THz detectors sensitive to Er doped fiber laser pulses at telecom wavelength of 1550 nm. These devices were fabricated from 1 μm thick (GaIn)(AsBi) layers grown on GaAs substrates and contained ~10% Bi.

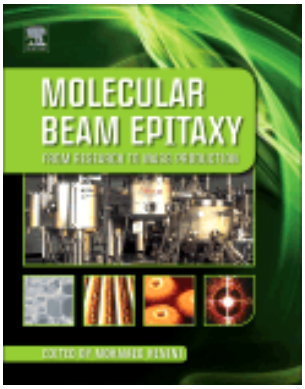
3.3. Main Dissemination Activities and Exploitation of Results

A wide range of activities were undertaken to ensure wide dissemination of the BIANCHO project. These have included publications and presentations to the scientific community, maintenance and development of the BIANCHO web site and further publicity. This included publication of a feature article concerning BIANCHO in one of the major industry publications, *Compound Semiconductor*, with the issue Editorial also devoted to the BIANCHO work (see: http://www.compoundsemiconductor.net/csc/adminpanel/uploads/magazine_images/csseptember2013.pdf). Further short features on BIANCHO were also published in the Financial Times and in EETimes-Europe – see http://www.electronics-eetimes.com/en/a-roadmap-for-cool-and-lossless-lasers-with-bismuth.html?cmp_id=7&news_id=222921884.

3.3.1 Meeting organisation

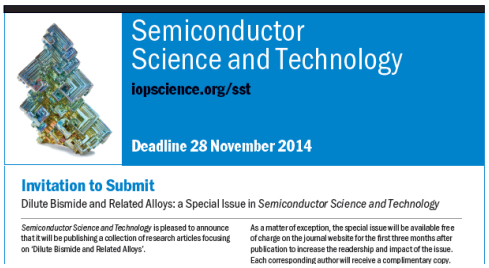
Our dissemination regarding the benefits of dilute bismide alloys was strongly supported through organisation of the second and fifth ***International Workshop on Bismuth-Containing Semiconductors*** from July 18-20, 2011 at University of Surrey and from July 20-23, 2014 at Tyndall in Cork (see www.bismides.org).

3.3.2 Presentations and Publications



We worked to ensure wide dissemination of the concepts behind the BIANCHO project throughout the full project period. This has been achieved through ***29 invited*** and ***78 contributed*** conference presentations being made over the 4 years of the project. ***26 refereed journal*** publications and ***10 conference journal*** papers were also published during the project, with further publications now submitted and/or in press. BIANCHO partners also prepared ***4 book chapters***, including two chapters in the first book reviewing dilute bismide alloys (Springer October 2013), as well as further chapters in a handbook on MBE growth (Elsevier) and in a book on "Excitonic and Photonic Processes in Materials". A full list of publications and of presentations for the project are included in Section A in this report.

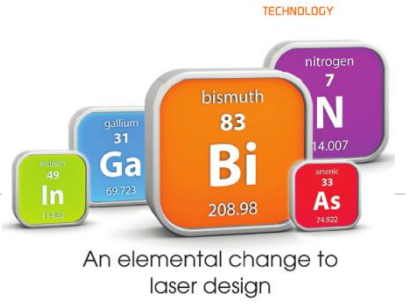
3.3.3 First bismide-related journal special issue



BIANCHO partners proposed to the IoP journal Semiconductor Science and Technology that it is now timely to publish a Special Issue of the journal devoted to Dilute Bismide and Related Alloys. This Special Issue includes 4 guest editors: BIANCHO partners Eoin O'Reilly and Stephen Sweeney, Shumin Wang (Shanghai) and Joshua Zide (University of Delaware). This is the first ever journal special issue focused on dilute bismide alloys, reflecting the major steps forward made in the development and understanding of these alloys over the course of the BIANCHO project.

3.3.4 BIANCHO Web Site and Press Activity

The BIANCHO project featured in the press on several occasions, including articles in the Financial Times and in EETimes-Europe, as well as in national media in Lithuania. The team was approached by *Compound Semiconductor* magazine to publish a feature on the



BIANCHO project, which appeared during year 4 in the August/September 2013 issue of the magazine. The magazine Editorial highlighted the work in BIANCHO, including comment that the BIANCHO consortium is "***trailblazing***", noting that "the promise of telecom lasers that are free from cooling is incredibly appealing" and would lead to "substantial energy savings*".*

The BIANCHO web site www.biancho.org was set up in the first months of the project, to promote and provide information on the project to a wide audience. The website consists of the following parts: 1) Project News and Overview; 2) Partners; 3) Science &Technology; 4) Publications; 5) Press Release; and 6) Workshops.

We promoted the BIANCHO website through a variety of means. This included dissemination on relevant discussion groups (e.g. Compound Semiconductor on LinkedIn) as well as through additional links from external sites, and inclusion of the site on partner presentations. There was a strong growth in hits for the BIANCHO site over the first 3 years of the project, followed by a relatively steady level of hits in year 4, as illustrated in Figure 27. The top left panel in figure 27 shows a graph of site hits as of 20th September 2011 (peak number of monthly hits 721), the top right panel shows the hits over the 12 months to 2 August 2012 (peak value 1415), the bottom left panel shows the hits to 1 October 2013 (peak number 2805), while the bottom right panel shows the hits over 12 months to 16 July 2014 (peak number 2471). It is difficult to correlate peaks and troughs in Figure 27 with particular events, but the increased hit rate for August and September 2013 are likely to be associated with the publication of the BIANCHO article in Compound Semiconductor.

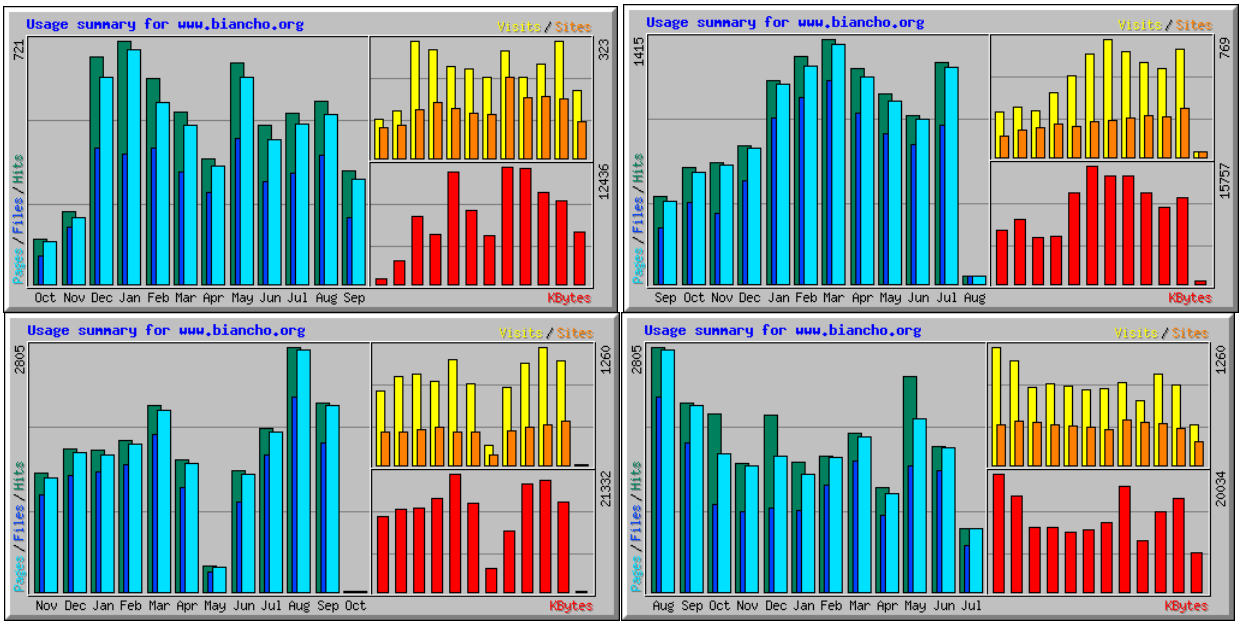


Figure 27: BIANCHO Web site hits as of 20th September 2011(top panel) 2nd August 2012 (second panel), 1st October 2013 (third panel) and 16 July 2014 (bottom panel).

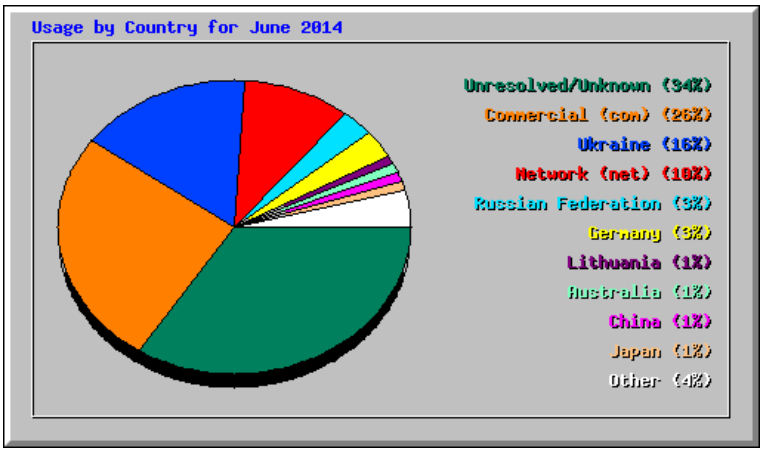


Figure 28: BIANCHO Web site hits by country and domain type in June 2014

Figure 28 shows the usage by country and domain type for June 2014, the month before the project hosted the 5th International Workshop on Bismuth-containing Semiconductors. Of addresses that can be resolved, it can be seen that the site attracted a broad range of interest, probably correlated with the broad range of countries that were represented at the 5th Bismide Workshop in July 2014.

The overall activity displayed in figures 1 and 2 indicate that the BIANCHO website acted as a valuable tool to disseminate the project. As the project results advanced, we used in particular the front page to promote the project achievements and highlights. The web pages also played an important role in promoting the 5th International Bismide Workshop in July 2014.

Overall, the web site was just one of the tools used to disseminate general awareness regarding BIANCHO. As described elsewhere in this report, we are pleased that the overall palette of methods used has enabled strong dissemination of BIANCHO; it is planned to maintain the web site following the end of BIANCHO as an ongoing dissemination tool and record of the project.

www.biancho.org

4 Use and dissemination of foreground

4.1 Dissemination of knowledge generated (Section A)

This section describes the dissemination measures, including any scientific publications relating to foreground generated during project execution. Information and public-domain results were facilitated through the following dissemination mechanisms:

- Project website
- Issuing of press releases
- Organization of events
- Publishing of technical publications (invited and contributed)
- Project posters
- Dissemination through electronic or printed media (mainstream technology websites and magazines)

Depending on the nature of the audience in each action, different aspects and information was conveyed for reaching the scientific community, the industry and the general public.

Table 1: List of scientific (peer reviewed) publications, STARTING WITH THE MOST IMPORTANT ONES

NO.	Title	Main author	Title of the periodical or the series	Number, date	Publisher	Place	Publication Year	Pages	Permanent identifiers (if available)	Open Access?
1	Electrical injection Ga(AsBi)/(AlGa)As single quantum well laser	K. Volz	Appl. Phys. Lett.	Vol. 102 (24)	Americam Institute of Physics	USA	2013	242115	http://dx.doi.org/10.1063/1.4822122	Yes
2	Tight-binding analysis of the electronic structure of dilute bismide alloys of GaP and GaAs	E.P. O'Reilly	Phys. Rev. B	Vol. 84 (24)	American Physical Society	USA	2011	245202	http://dx.doi.org/10.1103/PhysRevB.84.245202 arXiv:1111.4394 [cond-mat.mtrl-sci]	Yes
3	Band Engineering in Dilute Nitride and Bismide Semiconductor Lasers	E.P. O'Reilly	Semicond. Sci. Technol.	Vol. 27 (09)	Institute of Physics	UK	2012	094011	http://dx.doi.org/10.1088/0268-1242/27/9/094011 arXiv:1208.6441 [cond-mat.mtrl-sci]	Yes
4	Multiple quantum well laser diodes with more than 6% bismuth in Ga(AsBi)/GaAs quantum well layers	A. Krotkus	Electron. Lett.	Vol. 50 (16)	Institution of Engineering and Technology	UK	2014	1155	Doi: 10.1049/el.2014.1741	No
5	Physical properties and optimisation of GaBiAs/(Al)GaAs based near-infrared laser diodes grown by MOVPE with up to 4.4% Bi	S. J. Sweeney	J. Phys. D	Vol. 47	Institute of Physics	UK	2014	345103	http://dx.doi.org/10.1088/0022-3727/47/34/345103	Yes
6	Stucture and optical properties of InGaAsBi with up to 7% bismuth	A. Krotkus	Appl. Phys. Express	Vol. 5 (01)	Institute of Physics	UK	2012	015503	http://dx.doi.org/10.1143/APEX.5.015503	No
7	Bismide-nitride alloys: Promising for efficient light emitting devices in the near- and mid-infrared	S. J. Sweeney	Jour. Appl. Phys.	Vol. 113	American Inst. Physics	USA	2013	043110	http://dx.doi.org/10.1063/1.4789624	Yes
8	The electronic band-structure of GaAsBi/GaAs layers: Influence of strain and band anti-crossing	S. J. Sweeney	Jour. Appl. Phys.	Vol 111	American Inst. Physics	USA	2012	113108	http://dx.doi.org/10.1063/1.4728028	Yes

9	Temperature and Bi-concentration dependence of the band gap and spin-orbit splitting in InGaBiAs/InP semiconductors for mid-infrared applications	S. J. Sweeney	Appl. Phys. Lett.	Vol. 101	American Inst. Physics	USA	2012	221108	http://dx.doi.org/10.1063/1.4768532	Yes
10	Luminescence properties of dilute bismide systems	K. Volz, E.P. O'Reilly	Journal of Luminescence	Vol. 154	Elsevier	Netherlands	2014		http://dx.doi.org/10.1143/j.jlumin.2014.04.012	No
11	Growth and characterisation of Ga(NAsBi) alloy by metal organic vapour phase epitaxy	S. J. Sweeney, K. Volz,	Journal of Crystal Growth	Vol. 396	Elsevier	Netherlands	2014	7984	http://dx.doi.org/10.1016/j.jcrysgro.2014.03.038	Yes
12	Growth of Ga(AsBi) on GaAs by continuous flow MOVPE	K. Volz	Journal of Crystal Growth	Vol. 396	Elsevier	Netherlands		9599	http://dx.doi.org/10.1016/j.jcrysgro.2014.03.041	No
13	Migration-enhanced epitaxy of thin GaAsBi layers	K. Volz, A. Krotkus	Lithuanian Journal of Physics	Vol. 54 (02)	Lithuanian Academy of Sciences	Lithuania	2014	125-129	http://dx.doi.org/10.3952/lithjphys.54209	Yes
14	Growth and characterization of UTC photo-diodes containing $GaAs_{1-x}Bi_x$ absorber layer	A. Krotkus	Solid St. Electron	Vol. 99 (09)	Elsevier	Netherlands	2014	101-103	http://dx.doi.org/10.1016/j.sse.2014.04.042	No
15	Photoluminescence at up to 2.4 μm wavelengths from GaInAsBi/AlInAs quantum wells	A. Krotkus	Journal of Crystal Growth	Vol 391 (1 April)	Elsevier	Netherlands	2014	116120	http://dx.doi.org/10.1016/j.crysgro.2014.01.009	Yes
16	Atomistic tight-binding study of electronic structure and interband optical transitions in $GaBi_xAs_{1-x}$/GaAs quantum wells	E.P. O'Reilly	Appl. Phys. Lett.	Vol. 104	Americam Institute of Physics	USA	2014	071103	http://dx.doi.org/10.1063/1.4865827 arXiv:1402.0310 [cond-mat.mtrl-sci]	Yes
17	Localization effects and band gap of GaAsBi alloys	S. J. Sweeney	Phys.Stat.Sol	Vol. 251	Wiley	Germany	2014	12761281	http://dx.doi.org/10.1002/pssb.201350311	Yes
18	Optical and electronic processes in semiconductor materials for device applications	S. J. Sweeney	Excitonic and Photonic Processes in Materials Springer Series in Materials	Vol.203	Springer	Germany, USA	2015	253-297	http://link.springer.com/chapter/10.1007/978-981-287-131-2_9	No

			Science							
19	InGaAsBi alloys on InP for efficient near- and mid-infrared light emitting devices	S. J. Sweeney	Journal of Applied Physics	Vol. 114	American Institute of Physics	USA	2013	213103	http://dx.doi.org/10.1063/1.4837615	Yes
20	Derivation of 12 and 14-band k.p Hamiltonians for dilute bismide and bismide-nitride semiconductors	E.P. O'Reilly	Semicond. Sci. Technol	Vol. 28	Institute of Physics	UK	2013		http://dx.doi.org/10.1088/0268-1242/28/12/125025 arXiv:1310.7969 [cond-mat.mtrl-sci]	Yes
21	Impact of alloy disorder on the band structure of compressively strained GaBiAs	S. J. Sweeney, E.P. O'Reilly	Physical Review B	Vol. 87	Americal Physical Society	USA	2013	115104	http://dx.doi.org/10.1103/PhysRevB.87.115104 arXiv:1303.1070 [cond-mat.mtrl-sci]	Yes
22	12-band k.p models for dilute bismide alloys of (In)GaAs derived from supercell calculations	E.P. O'Reilly	Physica Status Solidi	Vol. 250	Wiley	Germany	2013	773778	http://dx.doi.org/10.1002/pssb.201200423 arXiv:1309.3305 [cond-mat.mtrl-sci]	Yes
23	Bismuth-containing III–V semiconductors: Epitaxial growth and physical properties",	S. J. Sweeney, K. Volz,	Chapter 7, Book Title: Molecular Beam Epitaxy, from Research to Application		Elsevier	Netherlands	2012	139158	ISBN: 978-0-12-387839-7 http://dx.doi.org/10.1016/B978-0-12-387839-7.00007-5	No
24	Theory of the Electronic Structure of Dilute Bismide Alloys: Tight-binding and k.p Models	E.P. O'Reilly	Chapter 3, Book Title: Bismuth-Containing Compounds;		Springer Series in Material Science	Germany	2013		ISBN: 978-1-4614-8120-1 http://dx.doi.org/10.1007/978-1-4614-8121-8_3	No
25	Bismide-Based Photonic Devices for Near- and Mid-Infrared Applications	S. J. Sweeney	Chapter 2, Book Title: Bismuth-Containing Compounds;	Vol.186	Springer Series in Material Science	Germany	2013	29-53	ISBN: 978-1-4614-8120-1 http://dx.doi.org/10.1007/978-1-4614-8121-8_2	No
26	Recombination mechanisms and band alignment of $GaAs_{1-x}Bi_x$/GaAs LEDs	S. J. Sweeney	Appl. Phys. Lett.	Vol. 100	American Institute of Physics	USA	2012	051105	http://link.aip.org/link/doi/10.1063/1.3681139?ver=pdfcov	Yes
27	Non-stoichiometric GaAsBi/GaAs (100) molecular beam epitaxy growth	S. J. Sweeney	J. Cryst. Growth	Vol.338	Elsevier	Netherlands	2012	5761	DOI: 10.1016/j.jcrysgro.2011.07.036 http://www.sciencedirect.com/science/article/pii/S0022024811009110	Yes

28	Room temperature photoluminescence enhancement in GaAsBi alloys	S. J. Sweeney	Phys. Stat. Solidi.C	Vol. 9	Wiley	Germany	2012	259	DOI: 10.1002/pssc.201100256 http://onlinelibrary.wiley.com/doi/10.1002/pssc.201100256/abstract	Yes
29	Temperature and pump power dependent photoluminescence characterization of MBE grown GaAsBi on GaAs	K. Volz	Journal of Materials Science: Materials in Electronics	Vol. 23	Springer	Germany	2012	1799	http://dx.doi.org/10.1007/s10854-012-0665-1	No
30	GaAsBi photoconductive terahertz detector sensitivity at long excitation wavelengths	A.Krotkus	Applied Physics Express	Vol. 5 (02)	Institute of Physics	UK	2012	022601	http://dx.doi.org/10.1143/APEX.5.022601	No
31	Thermal annealing effect on properties of GaBiAs	A.Krotkus	Phys. Status Solidi C	Vol. 9 (07)	Wiley	Germany	2012	1614	http://dx.doi.org/10.1002/pssc.201100700	No
32	Photoluminescence investigation of $GaAs_{1-x}Bi_x$/GaAs heterostructures	A.Krotkus	Thin Solid Films	Vol. 520	Elsevier	Netherlands	2012	6425	http://dx.doi.org/j.tsf.2012/06.047	No
33	MOVPE growth of Ga(AsBi)/GaAs multi quantum well structures	K. Volz	J. Cryst. Growth	Vol. 370	Elsevier	Netherlands	2013	186190	http://dx.doi.org/10.1016/j.jcrysgro.2012.07.002	No
34	Semiconductor investigation by terahertz radiation pulses	A.Krotkus	Terahertz Emitters, Receivers, And Applications III, Book Series: Proceedings of SPIE	Vol. 8496	SPIE	USA	2012	84960V-1	http://dx.doi.org/10.1117/12.929130	No
35	The effect of Bi composition to the optical quality of $GaAs_{1-x}Bi_x$	S. J. Sweeney	Appl. Phys. Lett.	Vol. 99	American Institute of Physics	USA	2011	042107	http://dx.doi.org/10.1063/1.3617461	Yes
36	Photoluminescence investigation of high quality $GaAs_{1-x}Bi_x$ on GaAs	S. J. Sweeney	Appl. Phys. Lett.	Vol. 98	American Institute of Physics	USA	2011	122107	http://dx.doi.org/10.1063/1.3565244	Yes
37	Thermal annealing effect on photoexcited carrier dynamics in $GaB_{ix}As_1$	A.Krotkus	Semiconductor Science and Technology,	Vol. 26 (08)	Institute of Physics	UK	2011	085033	http://dx.doi.org/10.1088/0268-1242/26/8/085033	No

Table 2: List of dissemination activities

NO.	Type of activities	Main leader	Title	Date/Period	Place	Type of audience	Size of audience	Countries addressed
1	Press Release	CIP	BIANCHO Launch	August 2010	UK	Medias		International readership
2	Workshop Organisation	Surrey	2nd International Workshop on Bismuth-Containing Semiconductors	July 2011	UK	Scientific Community	45	International attendance
3	Popular Press	Surrey	Financial Times article: "Laser redesign takes the heat off the internet"	13 July 2012	UK	General public		International readership
4	Trade Press	Tyndall	Compound Semiconductor magazine article and editorial	August/September 2013	UK	Technical trade		International readership
5	Workshop Organisation	Tyndall	5th International Workshop on Bismuth-Containing Semiconductors	July 2014	Ireland	Scientific Community	55	International attendance
6	Press Release	Tyndall	BIANCHO and Workshop story	July 2014	Ireland	Medias		International readership
7	Scientific Journal Special Issue	Tyndall	Special Issue of Semiconductor Science and Technology on Dilute Bismide Alloys	July 2014 – March 2015	UK	Scientific Community		International readership
8	Popular Press	FTMC	Article in popular science magazine Mokslas ir Technika "Atomic puzzles"	March 2013	Lithuania	General public		Lithuania
9	Invited Conference Presentation	Surrey	Electrically Injected GaAsBi Quantum Well Lasers	September 2014	24th IEEE International Semiconductor Laser Conference Spain	Scientific Community	200	International attendance
10	Invited Workshop Presentation	FTMC	Growth and characterisation of dilute Bi quantum wells for laser applications	July 2014	5th International Workshop on Bismuth-Containing Semiconductors Ireland	Scientific Community	55	International attendance
11	Invited Conference Presentation	Marburg	Metastable III/V semiconductors: growth mechanisms, structural peculiarities and device application	July 2014	International Conference on Metal Organic Vapour Phase Epitaxy 2014Switzerland	Scientific Community		International attendance
12	Invited Workshop Presentation	Surrey	III-Bismides: promising new materials for efficient photonic devices	June 2014	EXMATEC, Delphi Greece	Scientific Community	100	International attendance
13	Invited Conference Presentation	Tyndall	Dilute bismide materials and devices	May 2014	Compound Semiconductor Week 2014 France	Scientific Community	700	International attendance
14	Invited Workshop	Surrey	New directions in III-V semiconductors:	October 2013	SemiconNano 2013 Workshop	Scientific	50	International

	Presentation		Bismuth-containing structures for laser, detector and photovoltaic applications		US	Community		attendance
15	Invited Workshop Presentation	Tyndall	Valence band structure of dilute bismide alloys for optoelectronic device applications	September 2013	COSTMP0805 Final Meeting Turkey	Scientific Community	60	International attendance
16	Invited Workshop Presentation	Marburg	MOVPE growth of Ga(AsBi)/(AlGa)As heterostructures and laser diodes	September 2013	COSTMP0805 Final Meeting Turkey	Scientific Community	60	International attendance
17	Invited Workshop Presentation	Surrey	Bismide alloys for photovoltaics: a versatile new materials system	July 2013	Photovoltaics Workshop UK	Scientific Community	40	International attendance
18	Invited Workshop Presentation	Marburg	MOVPE growth of Ga(AsBi)/(AlGa)As hetero structures and laser diodes	July 2013	4th International Workshop on Bismuth-containing Semiconductors - Theory & Experiment US	Scientific Community	40	International attendance
19	Invited Workshop Presentation	Tyndall	Band structure engineering of dilute bismide alloys for optoelectronic device applications	July 2013	4th International Workshop on Bismuth-containing Semiconductors - Theory & Experiment US	Scientific Community	40	International attendance
20	Invited Workshop Presentation	FTMC	Dilute bismides for terahertz optoelectronic applications	November 2012	NATO Advanced Research Workshop on THz Imaging of CBRN and Explosives Turkey	Scientific Community		International attendance
21	Invited Conference Presentation	Surrey	Bismide alloys for Photonic Devices: Potential and Progress	September 2012	IEEE Photonics Society Annual Meeting US	Scientific Community	100	International attendance
22	Invited Conference Presentation	Surrey	Emerging materials for mid-infrared photonic devices	September 2012	Mid-Infrared Optoelectronic Materials and Devices US	Scientific Community	200	International attendance
23	Invited Conference Presentation	FTMC	Semiconductor investigations by THz radiation pulses	August 2012	SPIE Optics + Photonics. US	Scientific Community		International attendance
24	Invited Workshop Presentation	Surrey	Bismide alloys for near- and mid-infrared photonic devices	July 2012	3rd International Workshop on Bismuth-Containing Semiconductors Canada	Scientific Community	35	International attendance
25	Invited Workshop Presentation	FTMC	Growth and characterization of GaAsBi/GaAs and InGaAsBi/InP components for terahertz and mid-infrared applications	July 2012	3rd International Workshop on Bismuth-Containing Semiconductors Canada	Scientific Community	35	International attendance
26	Invited Conference Presentation	Surrey	New semiconductor approaches to energy efficient integrated photonics	June 2012	International Conference on Optical, Optoelectronic and Photonic Materials and Applications 2012. Japan	Scientific Community	100	International attendance
27	Invited Conference Presentation	Tyndall	Band engineering of dilute bismide and nitride alloys for efficient near- and mid-infrared semiconductor lasers	May 2012	EMRS Spring Meeting France	Scientific Community	Symposium – 80; conference -	International attendance

							2000	
28	Invited Conference Presentation	Surrey	Optical and band-structure properties of $GaAs_{1-x}Bi_x$ LEDs	July 2011	UK Semiconductors Sheffield UK	Scientific Community	300	International attendance
29	Invited Workshop Presentation	Marburg	Challenges and prospects of metastable III/V-materials grown by MOVPE	July 2011	2nd International Workshop on Bismuth containing Semiconductors: Theory, Simulation and Experiment UK	Scientific Community	35	International attendance
30	Invited Conference Presentation	Surrey	The potential role of Bismide alloys in future photonic devices	June 2011	23rd international Conference on Transparent Optical Networks (ICTON) Sweden	Scientific Community	600	International attendance
31	Invited Conference Presentation	Tyndall	Tight binding analysis of the electronic structure of dilute bismide and nitride alloys of GaAs	June 2011	23rd international Conference on Transparent Optical Networks (ICTON) Sweden	Scientific Community	600	International attendance
32	Invited Conference Presentation	Surrey	Novel III-Vs for "greener" Near- and Mid-infrared Photonic Devices	December 2010	Photonics Global Conference Singapore	Scientific Community	100	International attendance
33	Invited Conference Presentation	Surrey	Novel III-V Semiconductors for next generation Photonic Devices	August 2010	International Conference on Optical and Photonic Materials and Applications Hungary	Scientific Community	120	International attendance
34	Invited Workshop Presentation	FTMC	GaBiAs epitaxial layers for terahertz optoelectronic applications	July 2010	1st International Workshop on Bismuth-Containing Semiconductors US	Scientific Community	30	International attendance
35	Invited Workshop Presentation	Tyndall	Theory of the electronic structure of dilute bismide alloys	July 2010	1st International Workshop on Bismuth-Containing Semiconductors US	Scientific Community	30	International attendance
36	Invited Workshop Presentation	Marburg	Structural analysis of Bi-containing III/V-compound semiconductors and heterostructures	July 2010	1st International Workshop on Bismuth-Containing Semiconductors US	Scientific Community	30	International attendance
37	Invited Conference Presentation	FTMC	Dilute bismides and their application in optoelectronic devices	August 2010	12th International Conference-School Advanced Materials and Technologies Lithuania	Scientific Community		International attendance
	Conference and Workshop Contributed Presentations	**Full details of all presentations below can be found at website www.biancho.org**						
1	Conference	Tyndall	Theory of the electronic structure of the dilute bismide alloy GaBiAs	August 2014	International Conference on the Physics of Semiconductors (ICPS-2014) US	Scientific Community	900	International attendance
2	Conference	Surrey, Marburg	GaBiAs/(Al)GaAs as a promising material system for electrically pumped near-infrared laser diodes	July/August 2014	6th International Conference on Optical, Optoelectronic and Photonic Materials and	Scientific Community	200	International attendance

					Applications (ICOOPMA-2014) UK			
3	Workshop	Tyndall,	Alloy disorder effects in GaBiAs/GaAs single quantum wells	July 2014	5th International Workshop on Bismuth-Containing Semiconductors Ireland	Scientific Community	55	International attendance
4	Workshop	Tyndall	Theory of the enhancement of the electron effective g-factor in GaBiAs/GaAs epilayers	July 2014	5th International Workshop on Bismuth-Containing Semiconductors Ireland	Scientific Community	55	International attendance
5	Workshop	Marburg, Surrey	Bismide-nitrides for solar cell and related applications	July 2014	5th International Workshop on Bismuth-Containing Semiconductors Ireland	Scientific Community	55	International attendance
6	Workshop	Surrey	Properties of GaAsBi/GaAs quantum well structures with different Bi distribution profiles	July 2014	5th International Workshop on Bismuth-Containing Semiconductors Ireland	Scientific Community	55	International attendance
7	Workshop	Marburg, Surrey	Carrier recombination in GaBiAs/(Al)GaAs laser diodes	July 2014	5th International Workshop on Bismuth-Containing Semiconductors Ireland	Scientific Community	55	International attendance
8	Workshop	Tyndall	Experimental characterisation and determination of band-offsets in GaBiAs quantum well lasers	July 2014	5th International Workshop on Bismuth-Containing Semiconductors Ireland	Scientific Community	55	International attendance
9	Workshop	Surrey	Requirements for a GaAsBi 1eV sub-cell in a GaAs based multi-junction solar cell	July 2014	5th International Workshop on Bismuth-Containing Semiconductors Ireland	Scientific Community	55	International attendance
10	Workshop	Marburg	MOVPE growth of Ga(AsBi)/GaAs heterostructures using alternative sources	July 2014	5th International Workshop on Bismuth-Containing Semiconductors Ireland	Scientific Community	55	International attendance
11	Workshop	Tyndall	Theory of the electronic and optical properties of dilute bismide quantum well lasers	July 2014	5th International Workshop on Bismuth-Containing Semiconductors Ireland	Scientific Community	55	International attendance
12	Workshop	Surrey	Experimental and modelling study of InGaAsBi/InP alloys with up to 5.8% Bi, and with $\Delta so > Eg$	July 2014	5th International Workshop on Bismuth-Containing Semiconductors Ireland	Scientific Community	55	International attendance
13	Conference	Marburg, Surrey	Bismide-nitrides for solar cell and related applications	July 2014	UK Semiconductors 2014 UK	Scientific Community	350	International attendance
14	Conference	Tyndall	Experimental analysis of electrical injection Ga(AsBi)/(AlGa)As single quantum well laser	April/May 2014	Semiconductor and Integrated Optoelectronics (SIOE) conference UK	Scientific Community		International attendance
15	Conference	Marburg, Surrey	Properties of GaBiAs/(Al)GaAs based near-infrared laser diodes with up to 4.4% bismuth grown by MOVPE	April/May 2014	Semiconductor and Integrated Optoelectronics (SIOE) conference UK	Scientific Community	100	International attendance

16	Conference	Marburg, Surrey	Physical properties of GaAsBi/GaAs-based quantum well near-infrared lasers	April 2014	Photonics Europe Belgium	Scientific Community	200	International attendance
17	Conference	Marburg, Surrey	GaAsBi/GaAs semiconductor lasers: initial laser characteristics and future Prospects	February 2014	Photonics West 2014 US	Scientific Community	60	International attendance
18	Conference	Tyndall	Multi-scale modelling of the electronic structure of dilute bismide alloys	January 2014	TMCS-2014 (Theory, Modelling and Computational Methods for Semiconductors) UK	Scientific Community	50	International attendance
19	Workshop	Tyndall	Theory of the enhancement of the electron effective g-factor in GaBiAs/GaAs epilayers	January 2014	TMCS-2014 (Theory, Modelling and Computational Methods for Semiconductors) UK	Scientific Community	50	International attendance
20	Conference	Tyndall	Theory of dilute bismide alloys for high efficiency, uncooled telecomm lasers	September 2013	Photonics Ireland 2013 Ireland	Scientific Community	180	International attendance
21	Workshop	Marburg, Surrey	Temperature-dependent properties of electrically-pumped GaAsBi/GaAs quantum well lasers	July 2013	4th International Workshop on Bismuth-containing Semiconductors US	Scientific Community	40	International attendance
22	Workshop	Surrey	Investigation of Eg-Δso cross-over in InGaAsBi samples for (Bi < 5%)	July 2013	4th International Workshop on Bismuth-containing Semiconductors US	Scientific Community	40	International attendance
23	Workshop	Marburg, Surrey, Tyndall	GaAsN/GaAsBi type-II structures for mid-infrared photonic devices	July 2013	4th International Workshop on Bismuth-containing Semiconductors US	Scientific Community	40	International attendance
24	Conference	Surrey	Electronic band structure of InGaAsBi/InP: effects of Bi composition and temperature	July 2013	UK Semiconductors Conference, Sheffield UK	Scientific Community	350	International attendance
25	Conference	Surrey	Towards Auger Recombination Rate Calculations in GaAs(1-x)Bix Alloys using an Unfolded, Supercell, Tight-Binding Band Structure	July 2013	UK Semiconductors Conference, Sheffield UK	Scientific Community	350	International attendance
26	Conference	Tyndall	Electronic Structure and Gain Engineering in Type-I GaBiAs and GaBiNAs Quantum Well Devices	July 2013	UK Semiconductors Conference, Sheffield UK	Scientific Community	350	International attendance
27	Conference	Marburg, Surrey, Tyndall	Band properties of GaAsN/GaAsBi type-II structures on GaAs	July 2013	UK Semiconductors Conference, Sheffield UK	Scientific Community	350	International attendance
28	Conference	FTMC	Characterization of GaAsBi layers by means of optical pump-probe technique	June 2013	42nd "Jaszowiec" International School and Conference on the Physics of Semiconductors Poland	Scientific Community		International attendance

29	Conference	Surrey	The potential of GaAsBiN for multi-junction solar cells	June 2013	39th Photovoltaics Specialists Conference US	Scientific Community	2000	International attendance
30	Conference	Tyndall	Theoretical investigation of the gain characteristics of dilute bismide and bismide-nitride quantum well lasers	April 2013	Semiconductor and Integrated OptoElectronics (SIOE) Conference UK	Scientific Community	120	International attendance
31	Conference	Surrey	Unfolding the Bandstructure of GaBi(1-x)As(x) Alloys	April 2013	Semiconductor and Integrated OptoElectronics (SIOE) Conference UK	Scientific Community	120	International attendance
32	Conference	FTMC	THz Time-Domain-Spectroscopy systems based on photoconductive components made from GaAsBi	February/March 2013	International Conference on Semiconductor Mid-IR Materials and Optics SMMO2013 Poland	Scientific Community		International attendance
33	Workshop	Tyndall	Band structure engineering in dilute bismide semiconductor lasers	September 2012	50th Anniversary Laser Diode Meeting, Coventry UK	Scientific Community	35	International attendance
34	Conference	Tyndall	Theory of the electronic structure of dilute bismide and bismide-nitride alloys of GaAs	September 2012	24th General Conference of the EPS Condensed Matter Division UK	Scientific Community	950	International attendance
35	Conference	Tyndall	Theory of the electronic structure of dilute bismide and bismide-nitride alloys of GaAs: Tight-binding and **k.p** models	July/August 2012	31st International Conference on the Physics of Semiconductors Switzerland	Scientific Community	1000	International attendance
36	Conference	Surrey	Temperature dependence of the band gap of InGaBiAs/InP	July/August 2012	31st International Conference on the Physics of Semiconductors Switzerland	Scientific Community	1000	International attendance
37	Conference	Surrey	Auger recombination suppression and band alignment in GaAsBi/GaAs	July/August 2012	31st International Conference on the Physics of Semiconductors Switzerland	Scientific Community	1000	International attendance
38	Conference	Surrey	Pressure dependence of GaAsBi/GaAs light emitting diodes	July 2012	The XV-th "High Pressure in Semiconductor Physics" HPSP-15 France	Scientific Community	90	International attendance
39	Conference	FTMC	MBE grown GaAsBi for optoelectronic applications	July 2012	International Conference on Superlattices, nanostructures and nanodevices Germany	Scientific Community		International attendance
40	Workshop	Surrey	Spectroscopic investigations of InGaBiAs/InP for mid-infrared applications	July 2012	3rd International Workshop on Bismuth-Containing Semiconductors: Growth, Properties and Devices Canada	Scientific Community	35	International attendance
41	Workshop	Surrey	The effect of growth parameters on the optical and structural quality of $GaAs_{1-x}Bi_x$ alloys	July 2012	3rd International Workshop on Bismuth-Containing Semiconductors: Growth, Properties and Devices Canada	Scientific Community	35	International attendance
42	Workshop	Marburg	Metal droplets in the growth of dilute	July 2012	3rd International Workshop on	Scientific	35	International

			bismide III/V alloys		Bismuth-Containing Semiconductors: Growth, Properties and Devices Canada	Community		attendance
43	Workshop	Tyndall	Tight-binding and **k.p** models for the electronic structure of InGaBiAs and GaBiNAs	July 2012	3rd International Workshop on Bismuth-Containing Semiconductors: Growth, Properties and Devices Canada	Scientific Community	35	International attendance
44	Workshop	Surrey	Optical and electrical properties of GaAs1-xBix/GaAs diodes	July 2012	3rd International Workshop on Bismuth-Containing Semiconductors: Growth, Properties and Devices Canada	Scientific Community	35	International attendance
45	Conference	Surrey	InGaBiAs/InP Semiconductors for Mid-Infrared Applications	July 2012	UK Semiconductors conference UK	Scientific Community	350	International attendance
46	Workshop	FTMC	Spectral measurements of the picosecond photoconductivity in semiconductors by THz radiation pulses	June 2012	3rd EOS Topical Meeting on Terahertz Science & Technology Czech Republic	Scientific Community		International attendance
47	Conference	Marburg	MOVPE Growth of Ga(AsBi)/GaAs Quantum Well Structures	May 2012	16th International Conference on Metal Organic Vapour Phase Epitaxy S Korea	Scientific Community		International attendance
48	Conference	FTMC	Long wavelength (˜ 3 µm) emission from InGaAsBi layers grown by molecular beam epitaxy	May 2012	EMRS Spring Meeting France	Scientific Community	80 - symposium	International attendance
49	Conference	Surrey	Growth and characterisation of GaAsBi p-i-n diodes	May 2012	EMRS Spring Meeting France	Scientific Community	80 - symposium	International attendance
50	Conference	Marburg	MOVPE growth of Ga(AsBi)/GaAs quantum well structures	May 2012	EMRS Spring Meeting France	Scientific Community	80 - symposium	International attendance
51	Conference	Tyndall	Band engineering of dilute bismide alloys for efficient near- and mid-infrared semiconductor lasers	April 2012	SPIE Photonics Europe Belgium	Scientific Community	1000	International attendance
52	Conference	Surrey	InGaBiAs/InP Semiconductors for Mid-Infrared Applications	April 2012	Semiconductor and Integrated OptoElectronics (SIOE) Conference UK	Scientific Community	120	International attendance
53	Conference	Surrey	Absorption characteristics of GaAs1-xBix/GaAs diodes in the near-infrared	April 2012	Semiconductor and Integrated OptoElectronics (SIOE) Conference UK	Scientific Community	120	International attendance
54	Conference	Surrey	Effects of rapid thermal annealing on GaAs1-xBix alloys	April 2012	Semiconductor and Integrated OptoElectronics (SIOE) Conference UK	Scientific Community	120	International attendance
55	Conference	Surrey	Carrier recombination and band	January 2012	Photonics West US	Scientific	80	International

			alignment of GaAs1-xBix emitters			Community		attendance
56	Workshop	Surrey	Bismide-alloys for near- and mid-IR lasers	September 2011	European Semiconductor Laser Workshop Switzerland	Scientific Community	100	International attendance
57	Workshop	Tyndall	Theory of the Electronic Structure of Novel Dilute Bismide Alloys (GaBiP & GaBiAs)	September 2011	3rd International Workshop on Epitaxial Growth and Fundamental Properties of Semiconductor Nanostructures Austria	Scientific Community		International attendance
58	Conference	Tyndall	Electronic structure of dilute bismide alloys: tight-binding and **K.P** analysis	September 2011	Photonics Ireland Ireland	Scientific Community	250	International attendance
59	Workshop	Surrey	Bismide-nitride alloys — promising candidates for near- and mid-infrared photonics	July 2011	2nd International Workshop on Bismuth-Containing Semiconductors: Theory, Simulation and Experiment UK	Scientific Community	40	International attendance
60	Workshop	Tyndall	Band anticrossing in dilute bismide alloys: Tight-binding and **k.p** analysis	July 2011	2nd International Workshop on Bismuth-Containing Semiconductors: Theory, Simulation and Experiment UK	Scientific Community	40	International attendance
61	Workshop	Tyndall	Electronic structure calculations for supercells containing dilute 'Bi' inside GaAs – an atomistic tight-binding approach	July 2011	2nd International Workshop on Bismuth-Containing Semiconductors: Theory, Simulation and Experiment UK	Scientific Community	40	International attendance
62	Workshop	Surrey	Spectral and Thermal Properties of $GaAs_{1-x}Bi_x$ LEDs	July 2011	2nd International Workshop on Bismuth-Containing Semiconductors: Theory, Simulation and Experiment UK	Scientific Community	40	International attendance
63	Workshop	Surrey, FTMC	Resonance of bandgap and spin orbit splitting in GaAsBi/GaAs Alloys	July 2011	2nd International Workshop on Bismuth-Containing Semiconductors: Theory, Simulation and Experiment UK	Scientific Community	40	International attendance
64	Workshop	FTMC	Optical characterization of GaBiAs/GaAs and InGaBiAs/InP epitaxial la	July 2011	2nd International Workshop on Bismuth-Containing Semiconductors: Theory, Simulation and Experiment UK	Scientific Community	40	International attendance
65	Workshop	Marburg	Growth of dilute nitride (GaIn)(NAs) on InP by MOVPE	July 2011	2nd International Workshop on Bismuth-Containing Semiconductors: Theory, Simulation and Experiment UK	Scientific Community	40	International attendance
66	Workshop	FTMC	Nonequilibrium carrier trapping and recombination in GaBiAs layers	July 2011	2nd International Workshop on Bismuth-Containing	Scientific Community	40	International attendance

					Semiconductors: Theory, Simulation and Experiment UK			
67	Workshop	FTMC	Structural Characteristics of Bi-containing III/V semiconductors	July 2011	2nd International Workshop on Bismuth-Containing Semiconductors: Theory, Simulation and Experiment UK	Scientific Community	40	International attendance
68	Workshop	Surrey	Mechanism of enhanced photoluminescence in $GaAs_{1-x}Bi_x$ alloys	July 2011	2nd International Workshop on Bismuth-Containing Semiconductors: Theory, Simulation and Experiment UK	Scientific Community	40	International attendance
69	Conference	FTMC	Thermal annealing effect on properties of GaBiAs	June 2011	16th Semiconducting and Insulating Materials Conference (SIMC) Sweden	Scientific Community		International attendance
70	Conference	Surrey	Composition dependence of photoluminescence of GaAsBi alloys on GaAs	May 2011	Conference on Compound Semiconductors Germany	Scientific Community	150	International attendance
71	Conference	Surrey	Physical properties of $GaAs_{1-x}Bi_x$ light emitting diodes	April 2011	Semiconductor and Integrated OptoElectronics (SIOE) UK	Scientific Community	120	International attendance
72	Conference	Surrey	Band gap – spin-orbit splitting cross-over observed in GaBiAs/GaAs layers with high Bismuth concentration	April 2011	Semiconductor and Integrated OptoElectronics (SIOE) UK	Scientific Community	120	International attendance
73	Conference	Surrey	Bismide-Nitride alloys for Mid-infrared Photonics	September 2010	10th International Conference on Mid-Infrared Optoelectronics: Materials and Devices (MIOMD-X) China	Scientific Community	200	International attendance
74	Conference	Surrey	Bismide-Alloys for Higher Efficiency Infrared Semiconductor Lasers	September 2010	IEEE International Semiconductor Laser Conference Japan	Scientific Community	250	International attendance
75	Conference	FTMC	Electron and trap dynamics in GaBiAs layers	August 2010	Fourth International Conference on Optical, Optoelectronics and Photonic Materials and Applications (ICOOPMA) Hungary	Scientific Community	140	International attendance
76	Conference	Surrey	The Potential of III-Bismides for Near- and Mid-IR Photonic Devices	July 2010	UK Semiconductors 2010 UK	Scientific Community	300	International attendance
77	Workshop	Surrey	Auger and optical loss suppression in near- and mid-IR emitters based upon Bismide alloys	July 2010	1st International Workshop on Bismuth-Containing Semiconductors US	Scientific Community	30	International attendance
78	Workshop	Surrey	Photoluminescence Investigation of Bulk GaAsBi on GaAs	July 2010	1st International Workshop on Bismuth-Containing Semiconductors US	Scientific Community	30	International attendance

4.2 Exploitation of knowledge generated

This section describes the exploitable foreground and provides the plans for exploitation.

4.2.1 Overview of BIANCHO exploitable knowledge

One of the key pieces of IP underpinning the BIANCHO project, namely the benefits of using bismide alloys to eliminate Auger recombination was filed for patent protection by the University of Surrey, prior to the start of the project.

Considerable know-how was generated by BIANCHO. Substantial progress was made in the growth of dilute bismide lasers, including hybrid growth where the active region was grown by MBE and the barrier and cladding layers by MOVPE, allowing us to extend demonstration of the world's first electrically pumped dilute bismide laser to bismuth compositions as high as 6%. Our overall knowledge and understanding of dilute bismide materials and their potential applications has also increased substantially. We submitted 3 patent applications during the project, as listed in Table 3 below.

BIANCHO targeted to develop temperature-insensitive telecom components, including lasers, semiconductor optical amplifiers (SOAs) and electro-absorption modulators. There is significant potential for commercial exploitation of these uncooled components both for telecoms applications, and as optoelectronic terahertz frequency range sources for telecoms and wider applications. The demonstration of the first electrically pumped dilute bismide laser by the BIANCHO consortium gives us clear world leadership in this field.

BIANCHO also targeted bismide-based components for efficient terahertz generation and detection. As part of the BIANCHO project FTMC undertook the fabrication and investigation of UTC-photodiodes including a GaBiAs absorbing layer. Their analysis showed that the low band offset between GaBiAs and GaAs makes these devices very suitable for use as ultrafast photodetectors for near-IR radiation, and also suitable for use in terahertz generation. Further modelling was also performed at FTMC outside of BIANCHO for device structure optimization. Growth and processing of the optimized structure has been undertaken. These devices demonstrated photosensitivities of 20 mA/W at 1064 nm. This is an order of magnitude larger than that for the initial devices, and comparable with those of p-i-n photodiodes with a bismide absorber layer (Bastiman, Sweeney, 2012). Based on these results and the wider analysis by FTMC, we conclude that dilute bismide UTC photodiodes represent a very promising route towards efficient THz generation. It should be noted that the SME TERAVIL, which is a spin-off company of the FTMC group, is already producing photoconductive THz emitters and detectors based on GaAsBi epitaxial layers as well as whole THz time-domain-spectroscopy systems using these components activated by Yb doped fiber laser pulses (see http://www.teravil.lt/products.php).

4.2.2 Patent Applications

Table 3 List of applications for patents

Type of IP Rights:	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant (s) (as on the application)
Patent	No		Lithuanian patent #6045 25/06/2014	Semiconductor Saturable Absorber Mirror (SESAM) on GaAs substrate with bismide absorber layers	Ramunas Adomavicius, Renata Butkute, Anton Koroliov, Arunas Krotkus, Vaidas Pacebutas
Patent	No		Lithuanian patent #6044 25/06/2014	Uni-Travelling-Carrier photodiode with bismide absorber layers	Arunas Krotkus, Andrejus Geizutis, Vaidas Pacebutas

4.2.3 Exploitable foreground

Table 4 : List of Exploitable Foreground

Type of Exploitable Foreground	Description of exploitable foreground	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
General advancement of knowledge	MBE GROWTH OF BISMIDE ALLOYS	NO		FUTURE ELECTRONIC AND OPTICAL DEVICES	1. TELECOMMS 2. SECURITY 3. INFORMATION SOCIETY	2019 2015 2016	KNOW-HOW NOT DEEMED PATENTABLE	BENEFICIARY 6 FTMC (OWNER)
General advancement of knowledge	MOVPE GROWTH OF BISMIDE ALLOYS	NO		FUTURE ELECTRONIC AND OPTICAL DEVICES	1. TELECOMMS 2. SECURITY 3. INFORMATION SOCIETY	2019 2019 2019	KNOW-HOW NOT DEEMED PATENTABLE	BENEFICIARY 2 MARBURG (OWNER)

Major progress has been made in know-how related to growth of dilute bismide alloys using both molecular beam epitaxy (MBE) and metalorganic vapour phase epitaxy (MOVPE) during BIANCHO.

Foreground from MBE growth already being exploited in production of THz components by FTMC spin-out Teravil. Further development of dilute bismide devices, in particular efficient telecom lasers, would have significant benefit. The device development would be exploited directly by component manufacturers such as CIP, with the components then being widely taken up and exploited in more energy-efficient telecom systems.

We have reviewed and judged that protection of the key know-how developed in MBE and MOVPE growth would not be easily policed, and therefore the know-how developed at this point does not warrant further protection by patent filing.

Further research is now necessary to develop growth to further extend range of bismide alloy compositions with good material quality.

The potential for dilute bismide materials remains high. The development of an Auger-free telecomm laser based on dilute bismide lasers would have major benefit across a range of applications where energy-efficient uncooled lasers are currently a holy grail, including applications in data centres, Si photonics and future 5G networks, to name but a few.

4.2.4 Project Exploitation Plans

Since the BIANCHO project ended in July 2014, there are a number of activities planned following the project completion that will further support dissemination of its activities. These include:

- further presentations at key conferences,
- a number of planned publications in key journals,
- use of BIANCHO know-how in education and training,

Conference presentations include an invited presentation at the 24th IEEE International Semiconductor Laser Conference, Palma de Mallorca in September. Given the significant scientific and technical progress over the last year, we also expect to publish at least another 10 BIANCHO-related journal publications during the remainder of 2014 and in 2015, including papers in the Special Issue of Semiconductor Science and Technology devoted to Dilute Bismide and Related Alloys.

Education and Training: All academic partners included outputs of BIANCHO in their education and training activities throughout the project period. TYNDALL, SURREY and MARBURG all made reference to the use of III-V alloys including dilute nitrides and bismides in their Solid State Physics undergraduate degree modules. They also offered undergraduate projects related to their BIANCHO activities. At FTMC three PhD students (A. Arlauskas, P. Svidovsky, and A. Koroliov) participated in BIANCHO research, one more PhD student (A. Bičiūnas) defended his thesis on GaBiAs based THz devices. Three PhD students participated in growth and structural characterization at MARBURG, two PhD (Z. Batool and S. Jarvis) and two Masters students (T. Wilson and Z. Bushell) were involved at SURREY and two PhD students at TYNDALL (Chris Broderick and Patrick Harnedy). Zoe Bushell from SURREY undertook her Masters research project at MARBURG on bismides, obtaining the highest mark in her cohort for her degree. She is now funded by a prestigious Marion-Redfern scholarship for PhD studies at SURREY. Chris Broderick was awarded the BOC Bursary (2013) for best PhD Student work at TYNDALL. BIANCHO-related know-how will continue to be used by all academic partners in further education and training.

Wider dissemination: The BIANCHO web site will be maintained and updated following the end of the project, with further external links also being sought for the site. Wide effort was also undertaken to publicise to relevant research communities the Special Issue of Semiconductor Science and Technology on Dilute Bismide Alloys, to ensure a strong impact for this Special Issue, and thereby also to maximise the wider impact of the BIANCHO project.

The inclusion of CIP as a partner within BIANCHO provided a route for development and exploitation of temperature insensitive components. CIP is now owned by Huawei, with a focus on development of products for Huawei. Huawei recognises the value of new materials technologies, and is working to increase its involvement with research within Europe. Huawei is committed to developing optoelectronic chip technology in Europe which will have the opportunity to be used in the global market by the largest global telecom equipment supplier.

FTMC undertook the fabrication and investigation of UTC-photodiodes including a GaBiAs absorbing layer in BIANCHO. Based on their results and wider analysis by FTMC, we conclude that dilute bismide UTC photodiodes represent a very promising route towards efficient THz generation. The SME TERAVIL, which is a spin-off company of the FTMC group, is already producing photoconductive THz emitters and detectors based on GaAsBi epitaxial layers as well as whole THz time-domain-spectroscopy systems using these components activated by Yb doped fiber laser pulses (see http://www.teravil.lt/products.php).

In summary, we have overall made major progress in the development of dilute bismide materials and devices. All partners are keen to see further development and exploitation of these alloys. To that end, the partners:

- are continuing to advocate the promises and the corresponding high exploitation potential of bismide-containing III-V compounds by publications, conference contributions and during topical events
- have disclosed and continue to disclose through publiactions and presentations relevant technical information on the growth of high-quality bismides in order to help other groups making progress in the field and so to promote the development of lasers (and related devices) with significant Auger recombination suppression
- will work on making dedicated contributions to enable funding of BIANCHO-related topics in future Calls of the European Commission, in particular under bottom-up disruptive research priorities.

5. Report on societal implications

A General Information *(completed automatically when **Grant Agreement number** is entered.*

Grant Agreement Number:	257594
Title of Project:	BIANCHO BIsmide And Nitride Components for High temperature
Name and Title of Coordinator:	Prof. Eoin O'Reilly

B Ethics

1. Did your project undergo an Ethics Review (and/or Screening)? • If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports? Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 *'Work Progress and Achievements'*	***No***
2. Please indicate whether your project involved any of the following issues (tick box) :	***NO***
RESEARCH ON HUMANS	
• Did the project involve children?	
• Did the project involve patients?	
• Did the project involve persons not able to give consent?	
• Did the project involve adult healthy volunteers?	
• Did the project involve Human genetic material?	
• Did the project involve Human biological samples?	
• Did the project involve Human data collection?	
RESEARCH ON HUMAN EMBRYO/FOETUS	
• Did the project involve Human Embryos?	
• Did the project involve Human Foetal Tissue / Cells?	
• Did the project involve Human Embryonic Stem Cells (hESCs)?	
• Did the project on human Embryonic Stem Cells involve cells in culture?	

• Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	
PRIVACY	
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	
• Did the project involve tracking the location or observation of people?	
RESEARCH ON ANIMALS	
• Did the project involve research on animals?	
• Were those animals transgenic small laboratory animals?	
• Were those animals transgenic farm animals?	
• Were those animals cloned farm animals?	
• Were those animals non-human primates?	
RESEARCH INVOLVING DEVELOPING COUNTRIES	
• Did the project involve the use of local resources (genetic, animal, plant etc)?	
• Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	
DUAL USE	
• Research having direct military use	No
• Research having the potential for terrorist abuse	No

C Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	Number of Women	Number of Men
Scientific Coordinator		1
Work package leaders	1	3
Experienced researchers (i.e. PhD holders)	2	9
PhD Students	1	8
Other	3	2

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	**12**
Of which, indicate the number of men:	11

D Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project? ✓ Yes ○ No

6. Which of the following actions did you carry out and how effective were they?

	Not at all effective				Very effective
❑ Design and implement an equal opportunity policy	○	○	○	○	○
❑ Set targets to achieve a gender balance in the workforce	○	○	○	○	○
✓ Organise conferences and workshops on gender	○	○	○	✓	○
❑ Actions to improve work-life balance	○	○	○	○	○

○ Other:

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

○ Yes- please specify

✓ No

E Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

✓ Yes- please specify

○ No

Surrey Open Days, school visits in Hampshire & Devon, UK

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

○ Yes- please specify

✓ No

F Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?

○ Main discipline: 1.2

○ Associated discipline: 1.3

○ Associated discipline**Error! Reference source not found.**: 2.2

G Engaging with Civil society and policy makers

11a Did your project engage with societal actors beyond the research community? *(if 'No', go to Question 14)* ✓ Yes ○ No

11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?

✓ No

○ Yes- in determining what research should be performed ○ Yes - in implementing the research ○ Yes, in communicating /disseminating / using the results of the project		
11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	○ ○	Yes No
12. Did you engage with government / public bodies or policy makers (including international organisations)		
○ No ○ Yes- in framing the research agenda ○ Yes - in implementing the research agenda ✓ Yes, in communicating /disseminating / using the results of the project		
13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers? ○ Yes – as a **primary** objective (please indicate areas below- multiple answers possible) ✓ Yes – as a **secondary** objective (please indicate areas below - multiple answer possible) ○ No		
13b If Yes, in which fields?		

Agriculture Audiovisual and Media Budget Competition Consumers Culture Customs Development Economic and Monetary Affairs Education, Training, Youth Employment and Social Affairs		Energy ✓ Enlargement Enterprise Environment External Relations External Trade Fisheries and Maritime Affairs Food Safety Foreign and Security Policy Fraud Humanitarian aid		Human rights Information Society✓ Institutional affairs Internal Market Justice, freedom and security Public Health Regional Policy Research and Innovation ✓ Space Taxation Transport	

13c If Yes, at which level? ○ Local / regional levels ✓ National level ✓ European level ✓ International level	

H Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	37
To how many of these is open access provided?	21
How many of these are published in open access journals?	0
How many of these are published in open repositories?	21
To how many of these is open access not provided?	
Please check all applicable reasons for not providing open access:	
❑ publisher's licensing agreement would not permit publishing in a repository ❑ no suitable repository available ❑ no suitable open access journal available ❑ no funds available to publish in an open access journal ❑ lack of time and resources ❑ lack of information on open access ✓ other: ……	

15. How many new patent applications ('priority filings') have been made? *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*		**3**
16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	**0**
	Registered design	**0**
	Other	**0**
17. How many spin-off companies were created / are planned as a direct result of the project?		**0**
Indicate the approximate number of additional jobs in these companies:		

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:

❑	Increase in employment, or	✓	In small & medium-sized enterprises
✓	Safeguard employment, or	❑	In large companies
❑	Decrease in employment,	❑	None of the above / not relevant to the project
❑	Difficult to estimate / not possible to quantify		

19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:	*Indicate figure:* *1*

Difficult to estimate / not possible to quantify	❑

I Media and Communication to the general public

20. As part of the project, were any of the beneficiaries professionals in communication or media relations?

○ Yes ✓ No

21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?

✓ Yes ○ No

22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?

✓	Press Release	✓	Coverage in specialist press
❑	Media briefing	❑	Coverage in general (non-specialist) press
✓	TV coverage / report	✓	Coverage in national press
❑	Radio coverage / report	✓	Coverage in international press
❑	Brochures /posters / flyers	❑	Website for the general public / internet
❑	DVD /Film /Multimedia	❑	Event targeting general public (festival, conference, exhibition, science café)

23 In which languages are the information products for the general public produced?

❑	Language of the coordinator	✓	English
❑	Other language(s)	✓	Lithuanian

***Question F-10*:** Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

FIELDS OF SCIENCE AND TECHNOLOGY

1. NATURAL SCIENCES

1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]

1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)

1.3 Chemical sciences (chemistry, other allied subjects)

1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)

1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2 ENGINEERING AND TECHNOLOGY

2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)

2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]

2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

3. MEDICAL SCIENCES

3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)

3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)

3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. AGRICULTURAL SCIENCES

4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)

4.2 Veterinary medicine

5. SOCIAL SCIENCES

5.1 Psychology

5.2 Economics

5.3 Educational sciences (education and training and other allied subjects)

5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. HUMANITIES

6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)

6.2 Languages and literature (ancient and modern)

6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group]